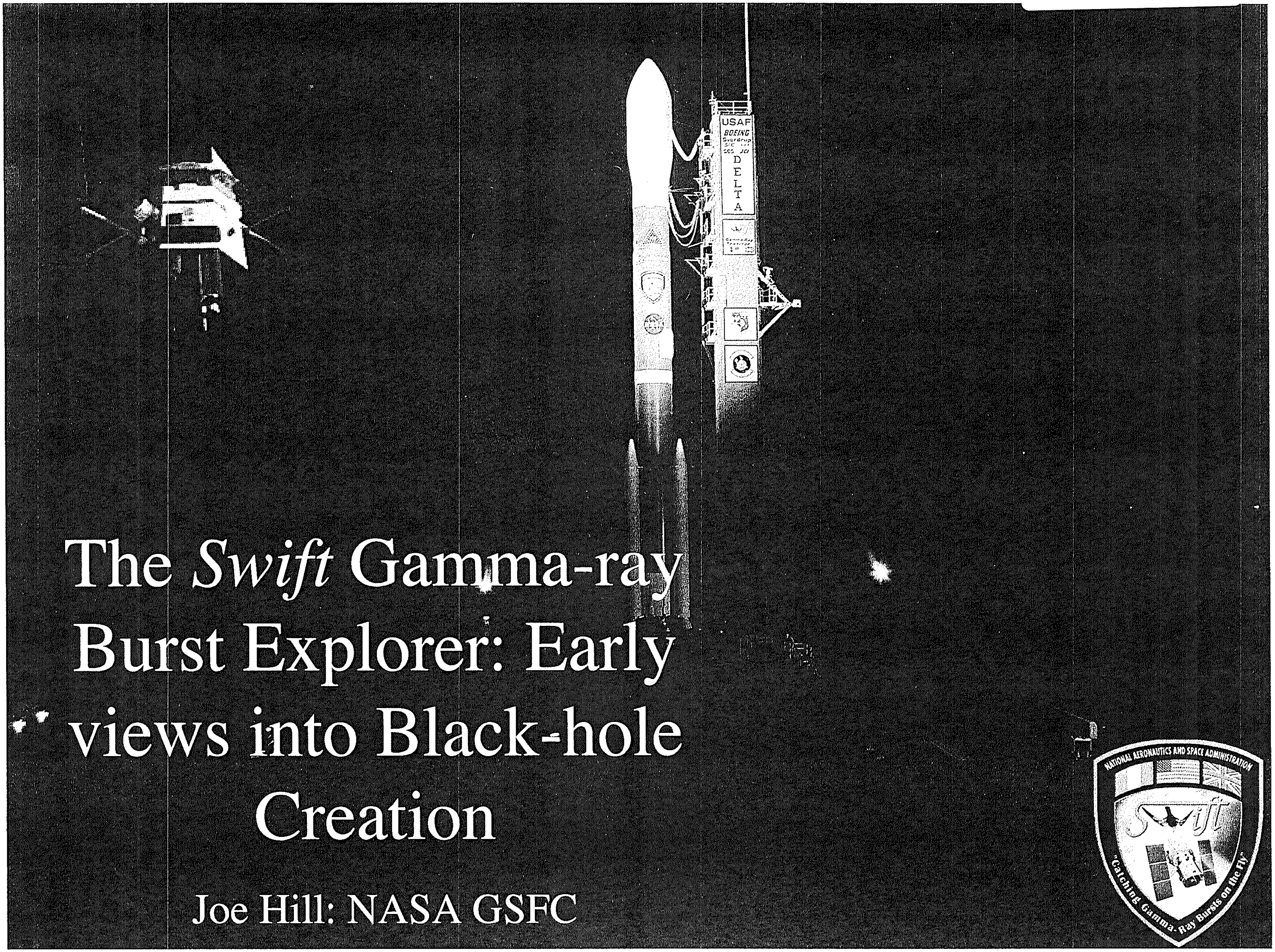

The *Swift* Gamma-ray Burst Explorer: Early views into Black-hole Creation
Joe Hill: NASA GSFC
USAF
BOEING
DELTA
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Swift
"Catching Gamma-Ray Bursts on the Fly"

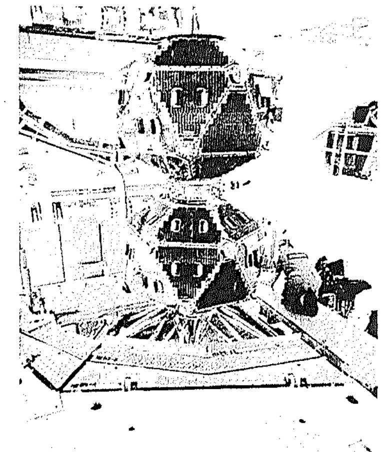
Overview

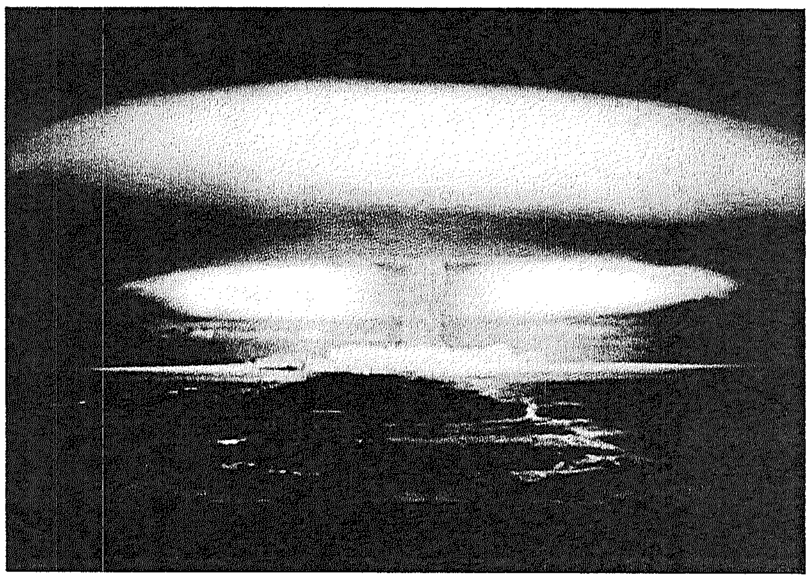
- The discovery of Gamma-ray Bursts
- The *Swift* Mission
- *Swift* afterglows - an early insight
- The detection of the elusive Short Burst
    - Catching the afterglow for the first time
- The detection of a huge explosion in the early universe
    -The most distant GRB ever detected
- GRB 060218
    -The beginnings of a SN?

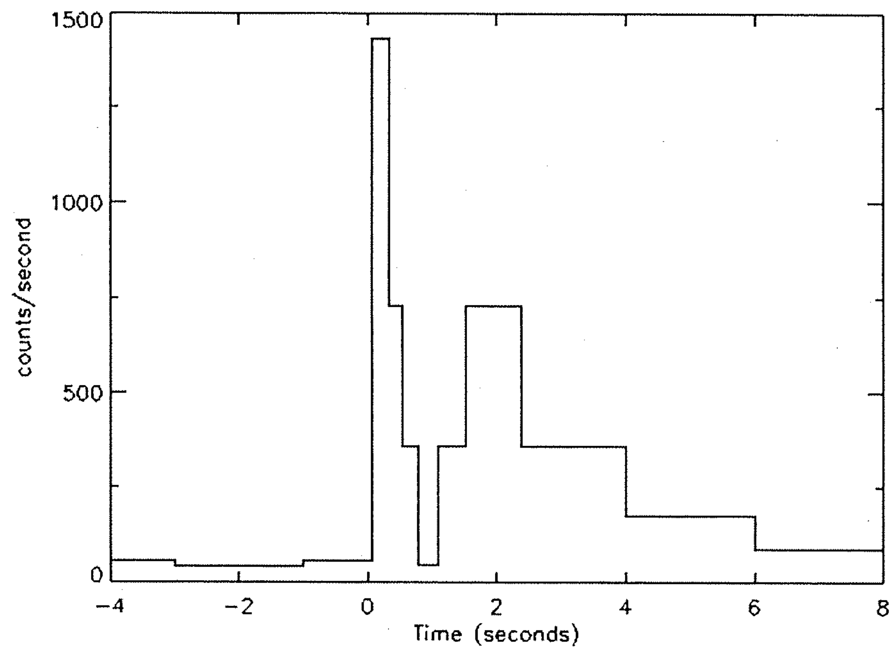
The Discovery of Gamma-ray Bursts: 1967

- Vela satellites launched in mid-1960s to monitor the Atmospheric Test Ban Treaty
  - Strange pulses discovered in 1969 by Ray Klebesadel of LANL

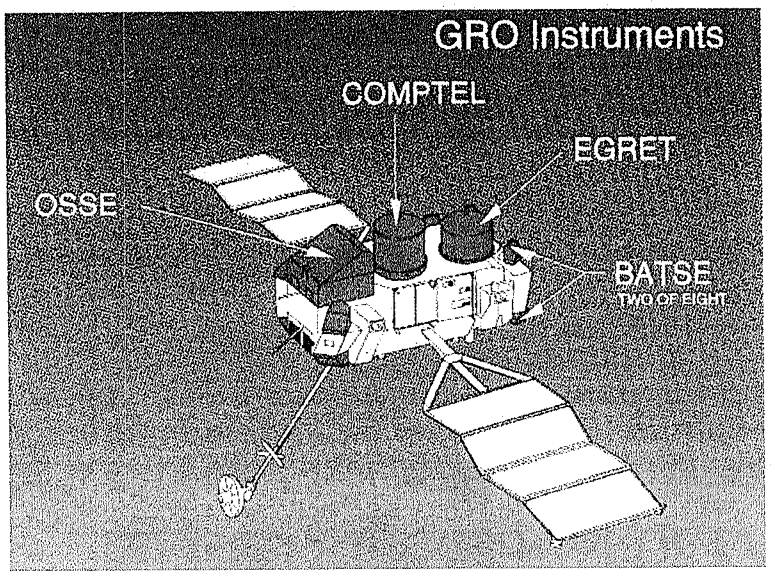
    Data classified until 1973



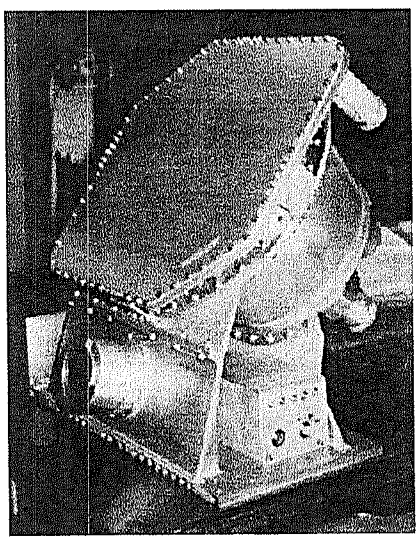


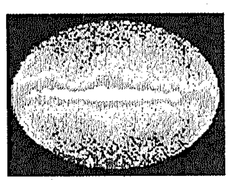


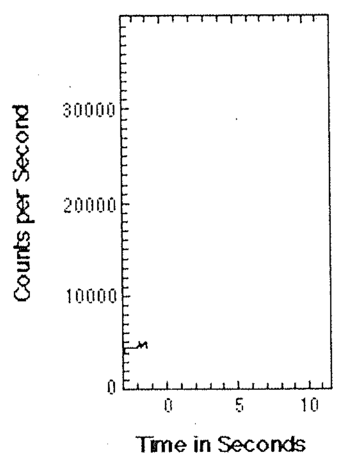
~25 Years after discovery: 1991



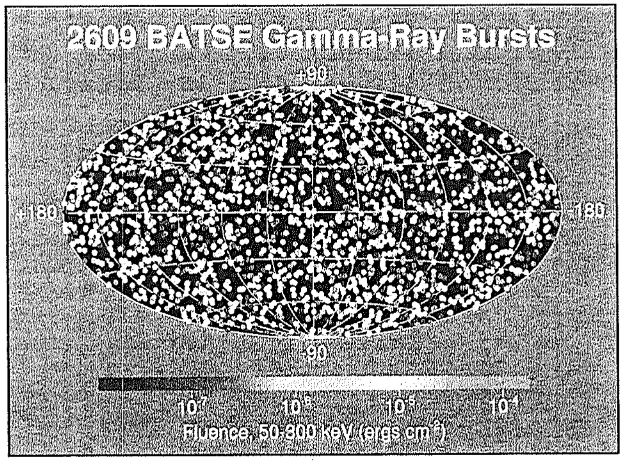
- Compton Gamma-Ray Observatory launched in April 1991
- BATSE: 2609 bursts in 8.5 years
  - Bursts are isotropic
  - Frequency ~ 1 burst per day
  - Not clear whether they are nearby or distant

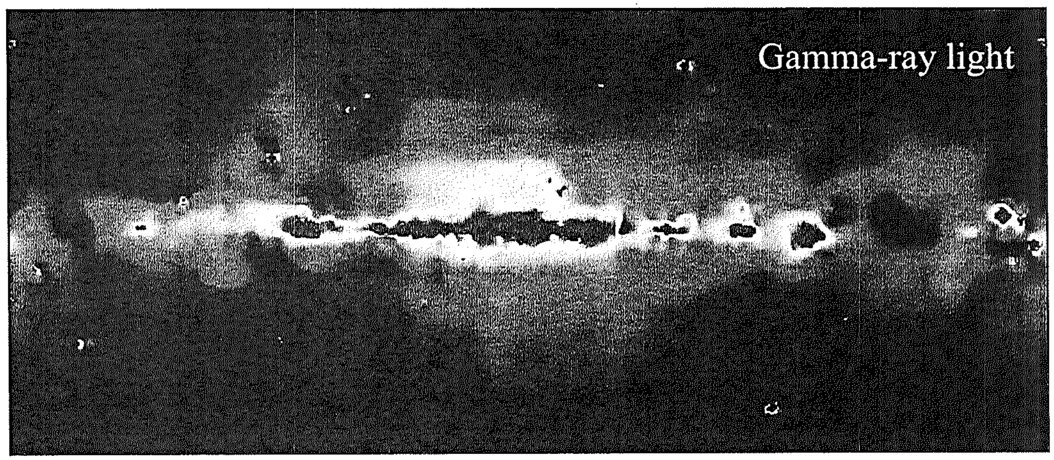


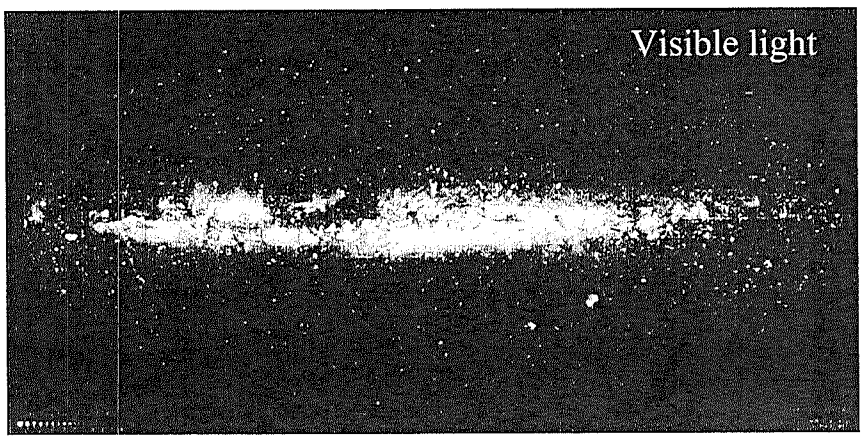


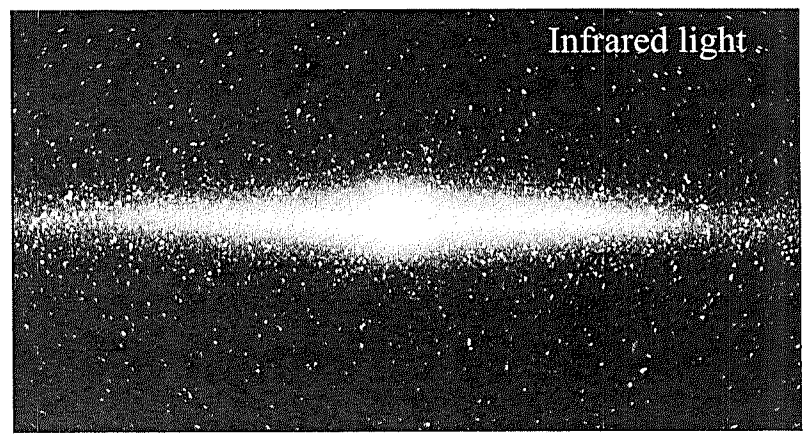


The celestial sky





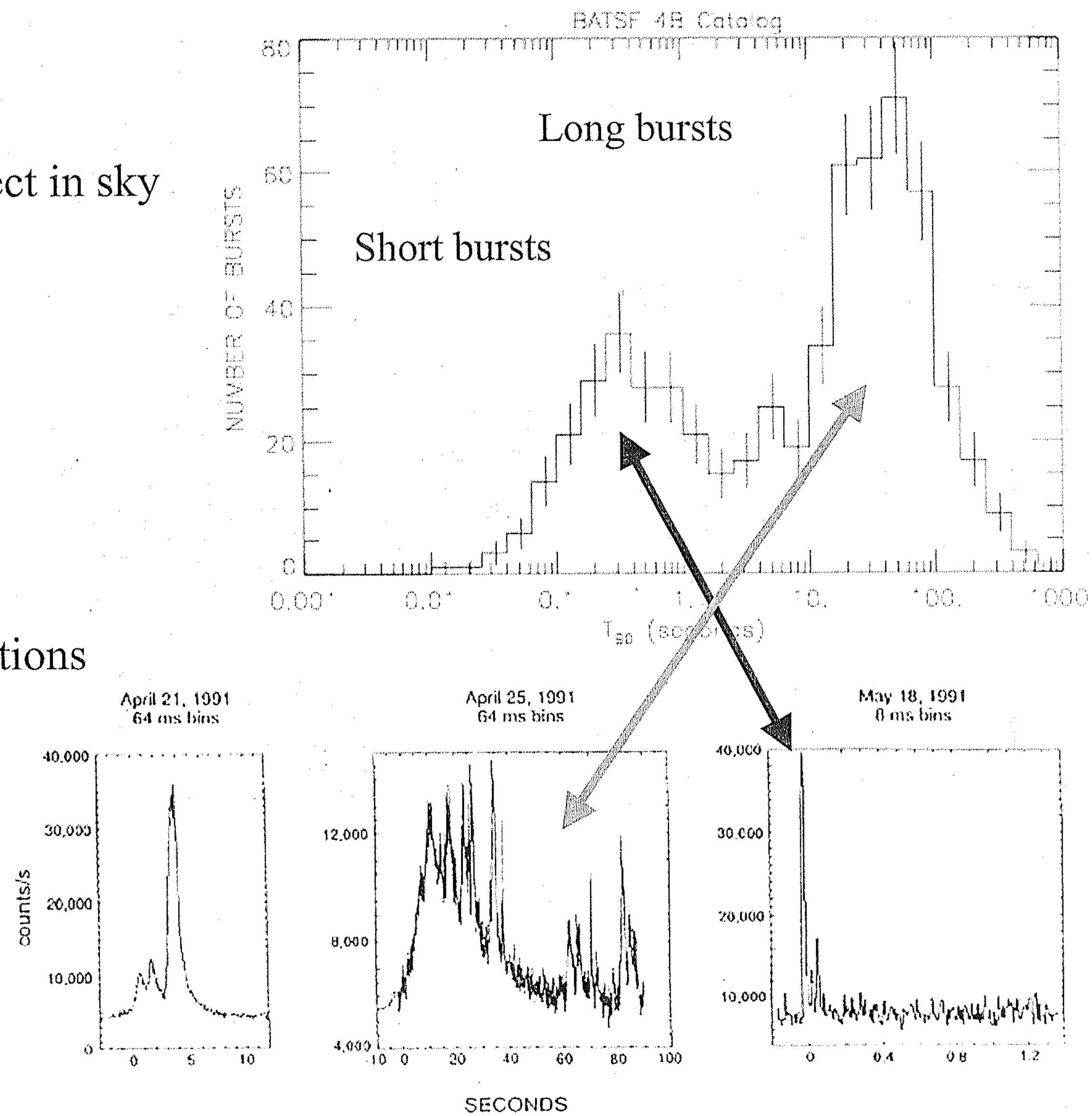




GRBs are distributed isotropically on the sky.

GRB Characteristics (BATSE)

- Characteristics:
  - About 1 per day
  - Powerful: brightest γ-ray object in sky
    - Typically 10^{51} ergs
  - Isotropic distribution
  - Finite Extent
  - Unique lightcurves
  - Bi-model distribution of durations



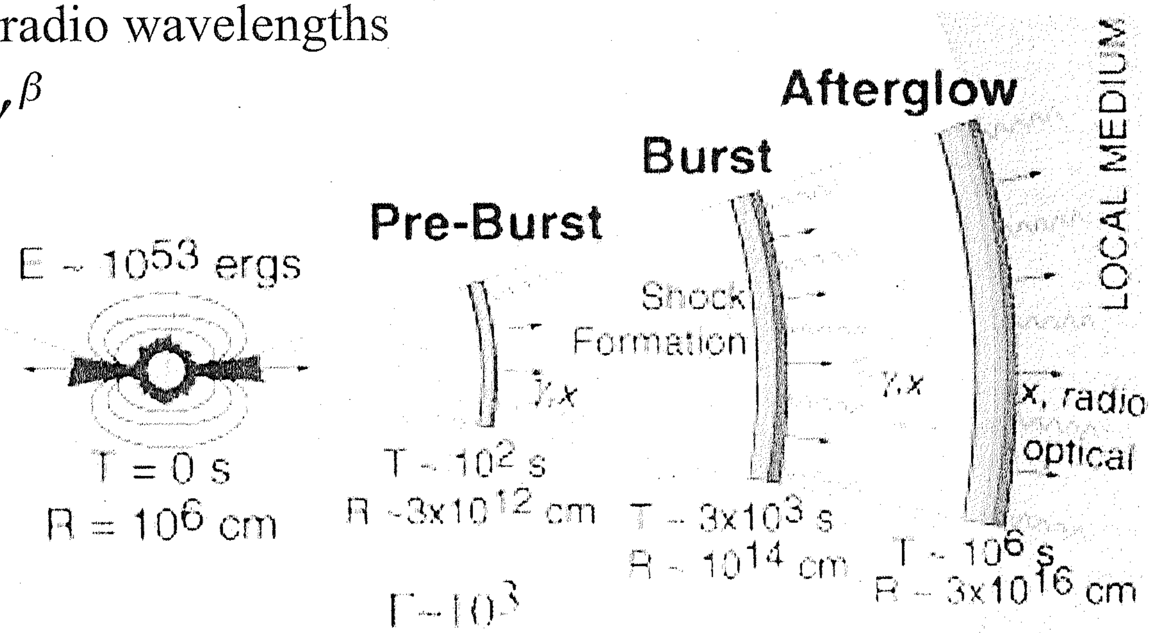
Theoretical Predictions

1992/1993: Emission mechanism: synchrotron emission from power-law distribution of electrons in highly relativistic outflows. Prediction of external shocks from ISM deceleration.

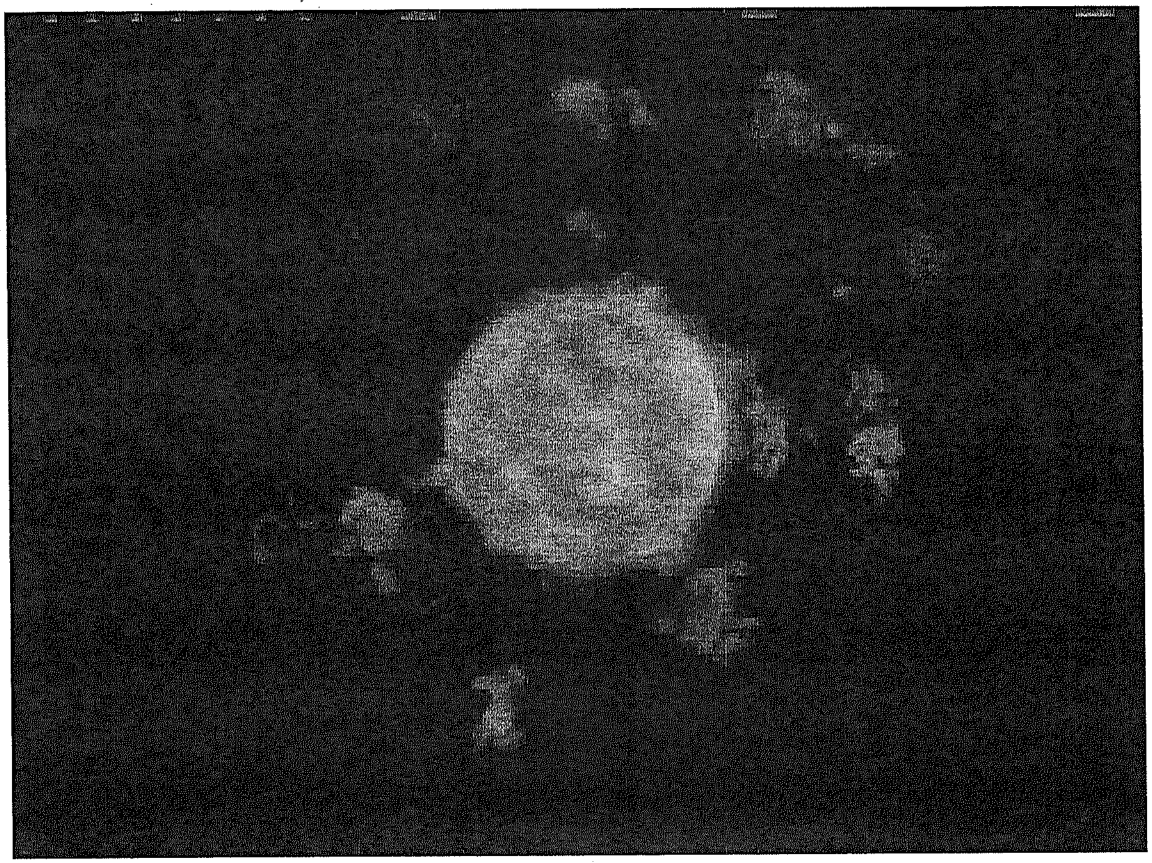
1994: Fireball-shock scenario involving colliding shells in the fireball out flow causing short timescale variability.

10th Feb 1997: Meszaros and Rees GRB relativistic fireball model published in ApJ; predicted broadband afterglows at optical, X-ray and radio wavelengths

$$F(\nu,t) \propto t^{\alpha}\nu^{\beta}$$

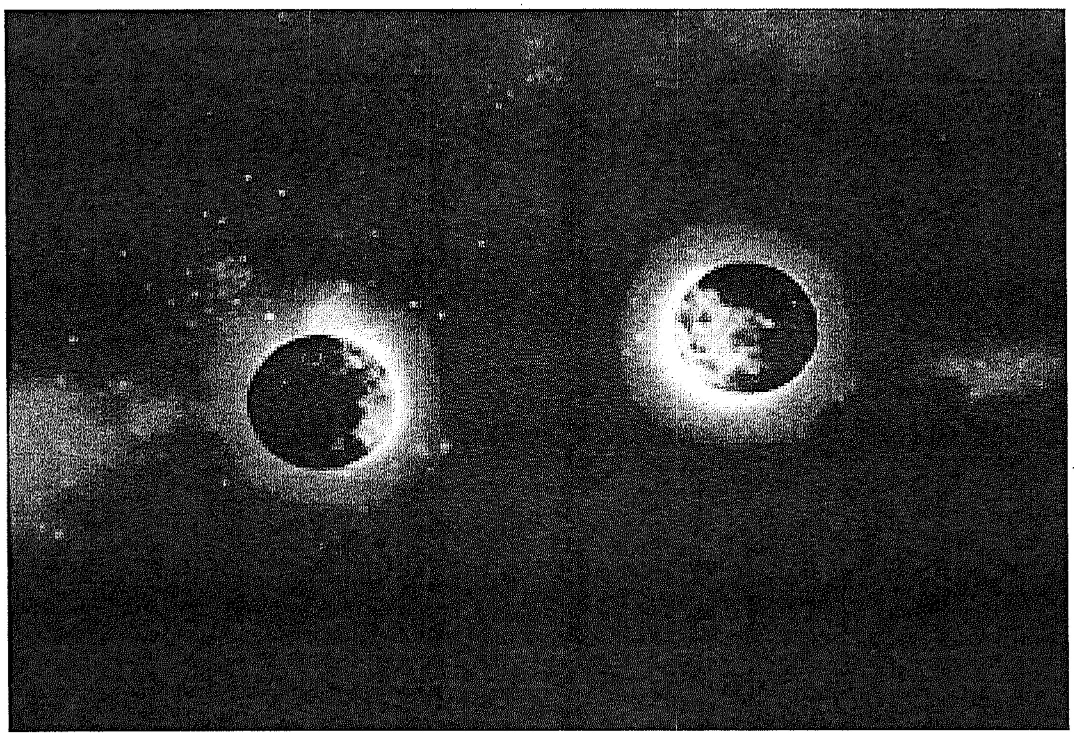


Hypernova



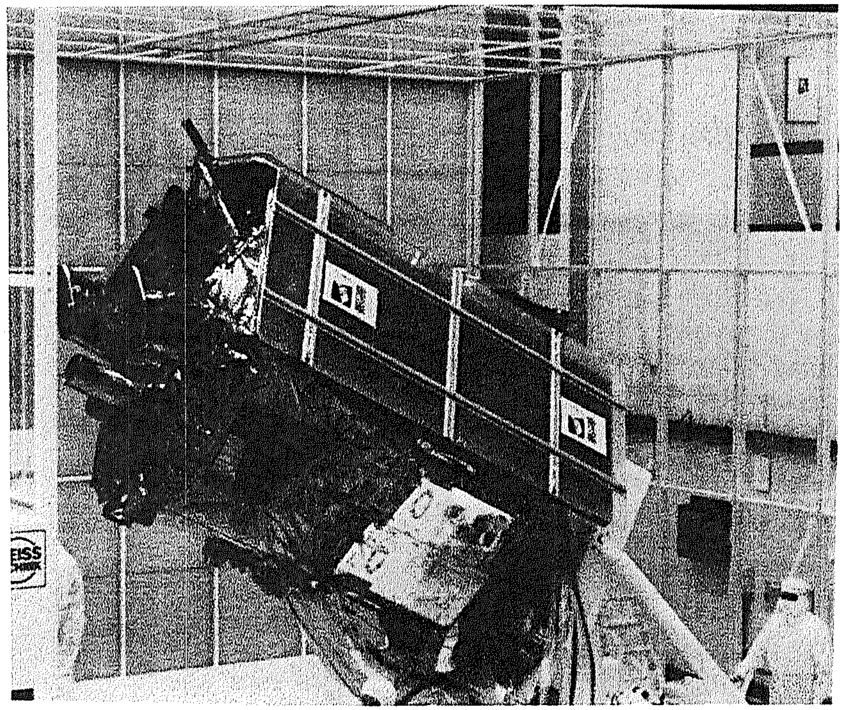
- The collapse of the core of a massive star to form a Black-Hole…..
- ~millions years before the explosion the fuel start to dwindle
- The envelope is lost
- Remaining fuel is depleted loosing radiation pressure
- Core collapses and forms a Black-Hole
- After ~few seconds streaming particle jets blast through the outer shells of the star

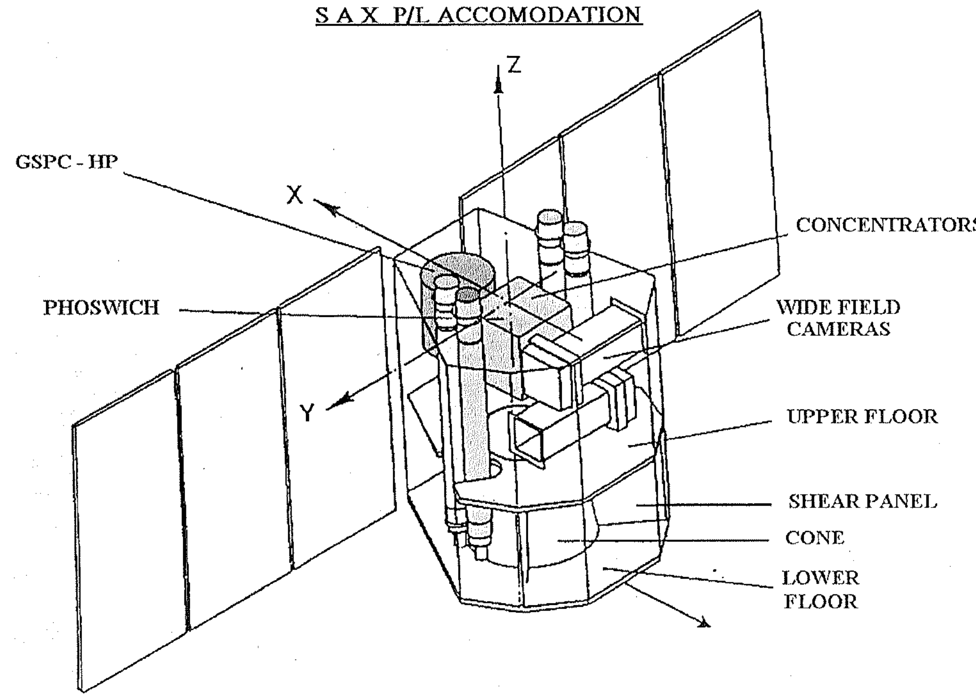
Binary Merger Theory



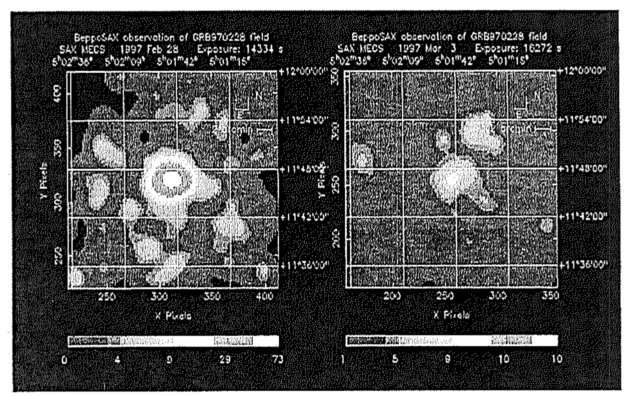
- Start with a NS-NS or an NS-BH pair orbiting each other…….
- The huge Gravitational force causes them to orbit each other with increasing velocities
- As they get closer together, they begin to become misshapen as they rip each other apart
- They finally merge in an instant, forming a Black-Hole shooting out jets of gamma-rays

Observational Breakthrough: 1997





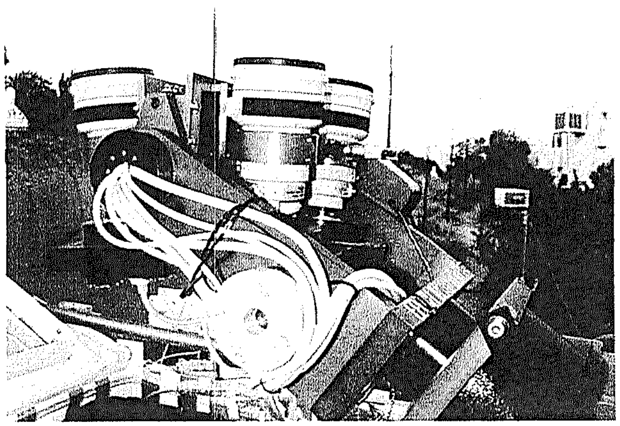
- Beppo-SAX makes the first X-ray image of a GRB afterglow.

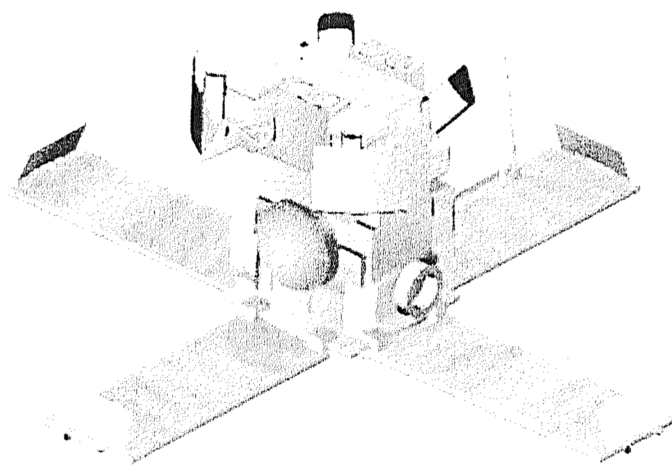


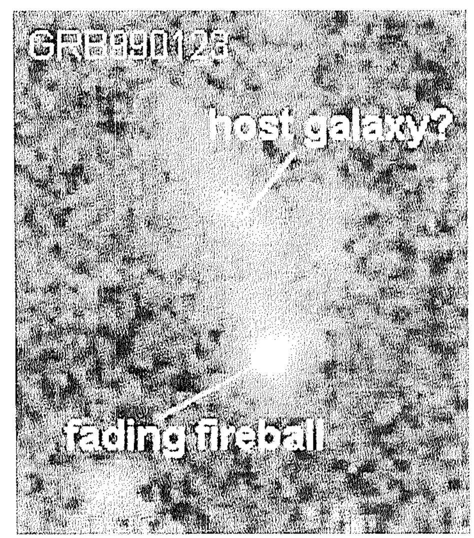
28 Feb 1997 3 March 1997

The Beppo-SAX / HETE-II era

- GRB 970228: first detection of X-ray and optical afterglows
- GRB 970508:
  - First redshift of GRB afterglow (Keck)
  - Also first radio detection of afterglow (VLA – scintillation)
    - Scintillation demonstrated that central source was compact => BH
    - Scintillation also proved superluminal expansion => fireball shock model
- GRB 990123: first optical observation of GRB (ROTSE)
  - "Biggest explosion since Big Bang"
- 55 afterglows discovered by Beppo-SAX and HETE-2
  - Typical delay of 6-8 hours in position determination

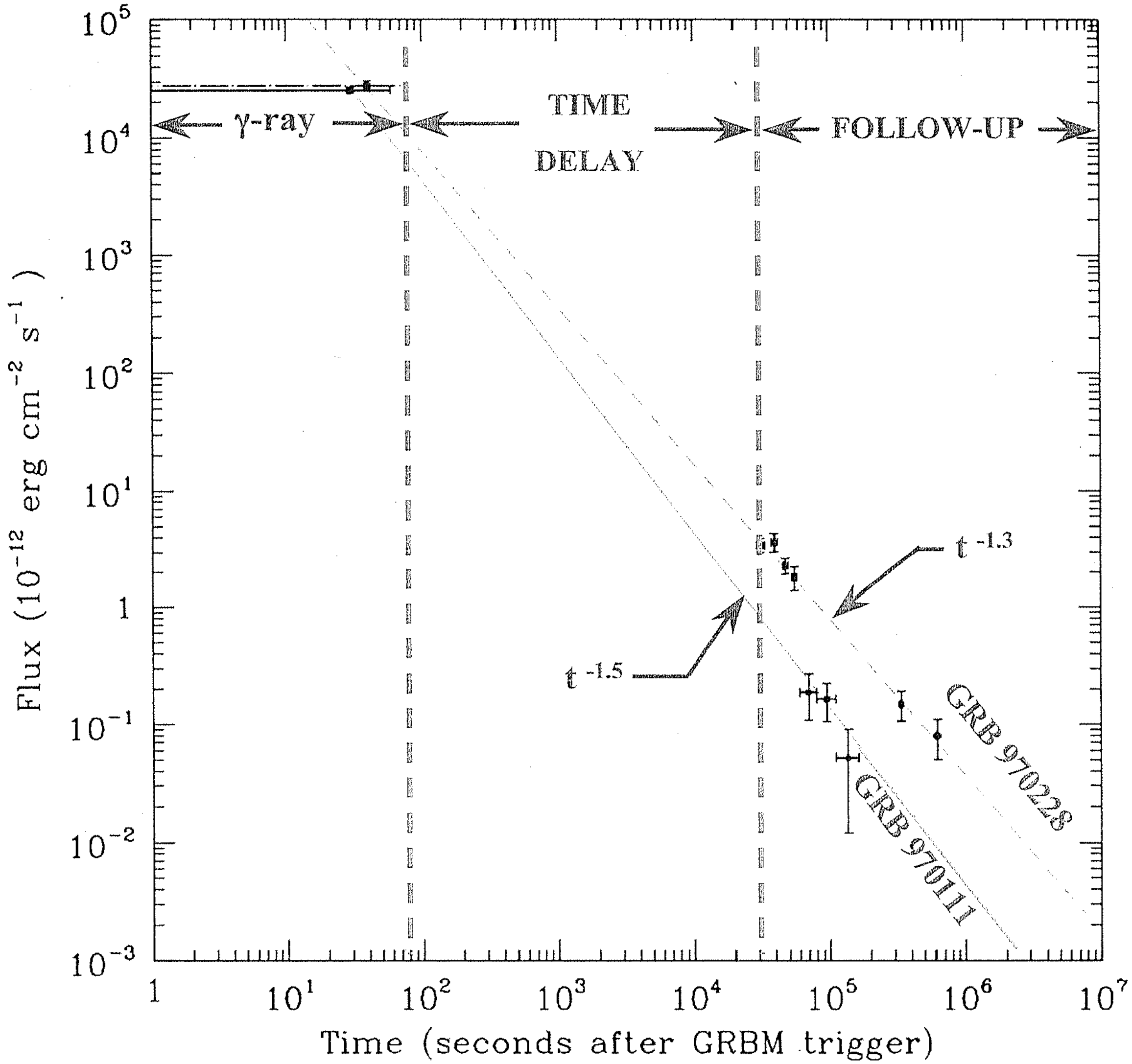




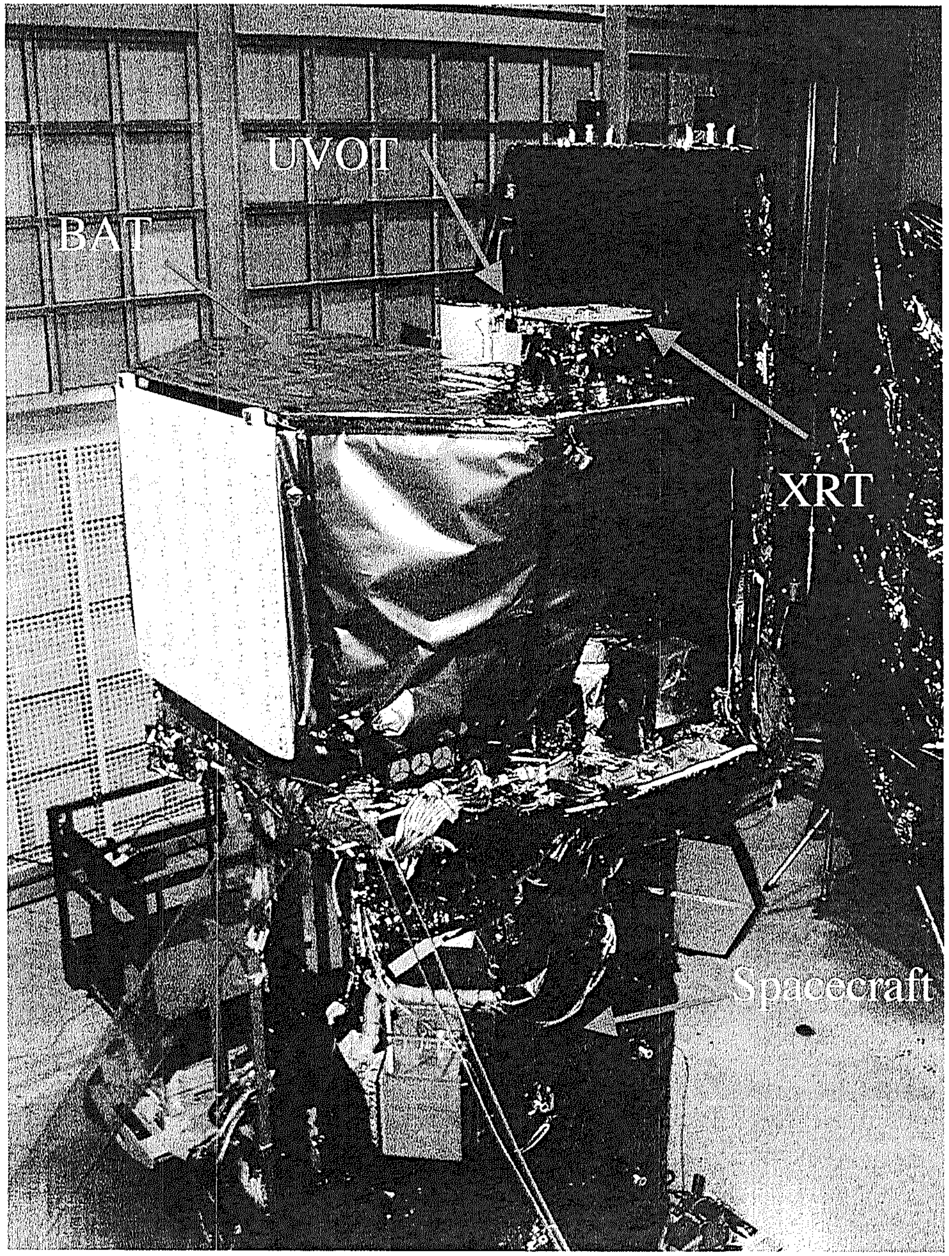


What Next?

- Need gamma-ray burst detector with large FoV
- Rapid follow-up ~minutes
  - X-ray Afterglow
  - Optical Afterglows
- Need to get localised positions rapidly to the ground

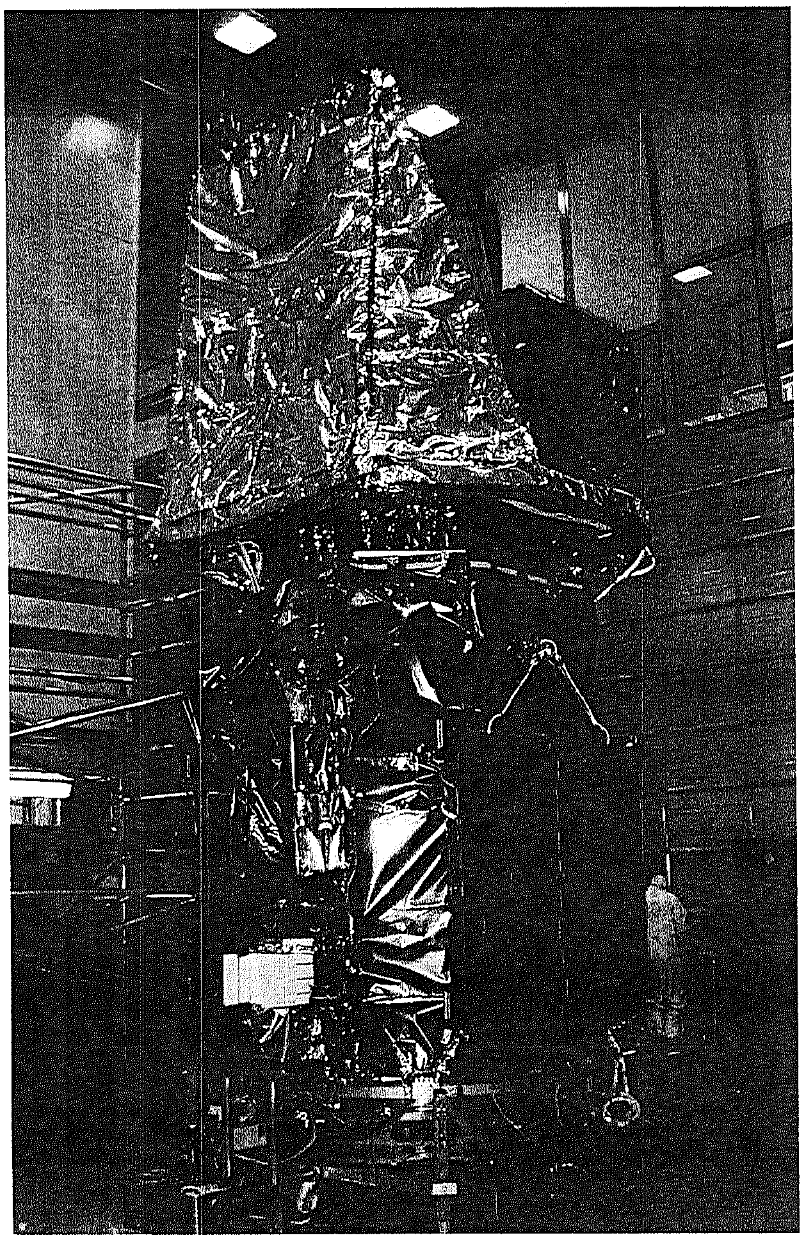


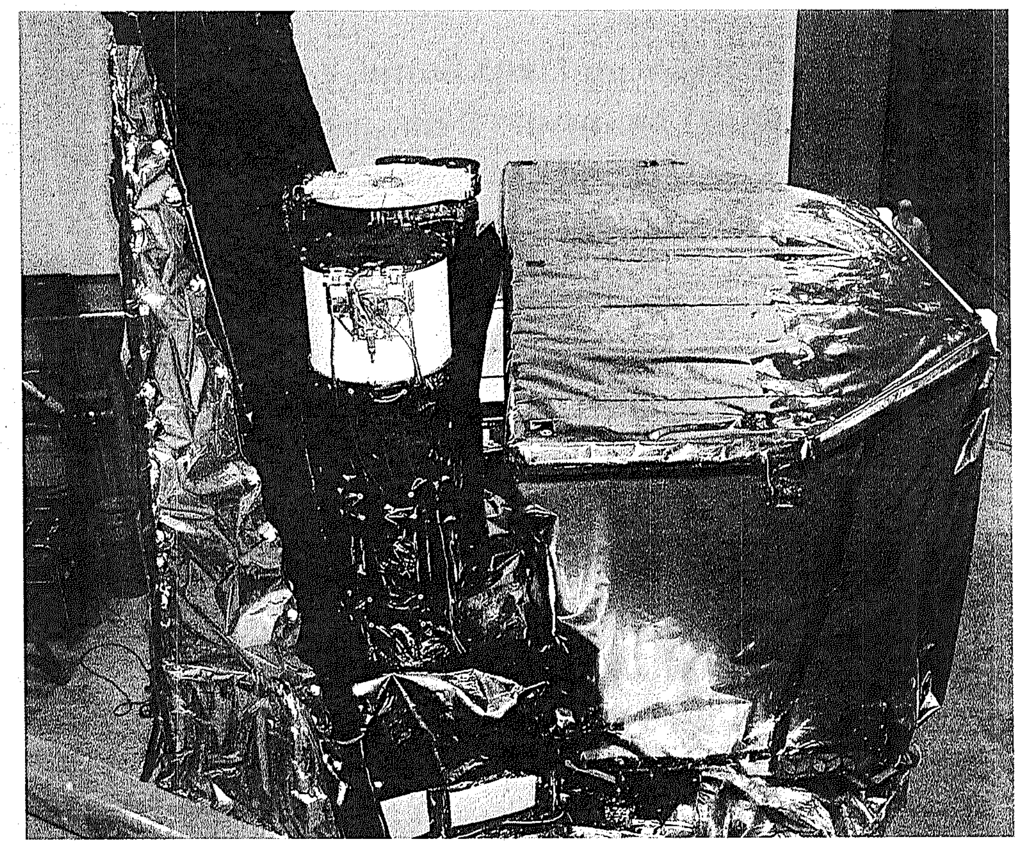
Swift Instruments



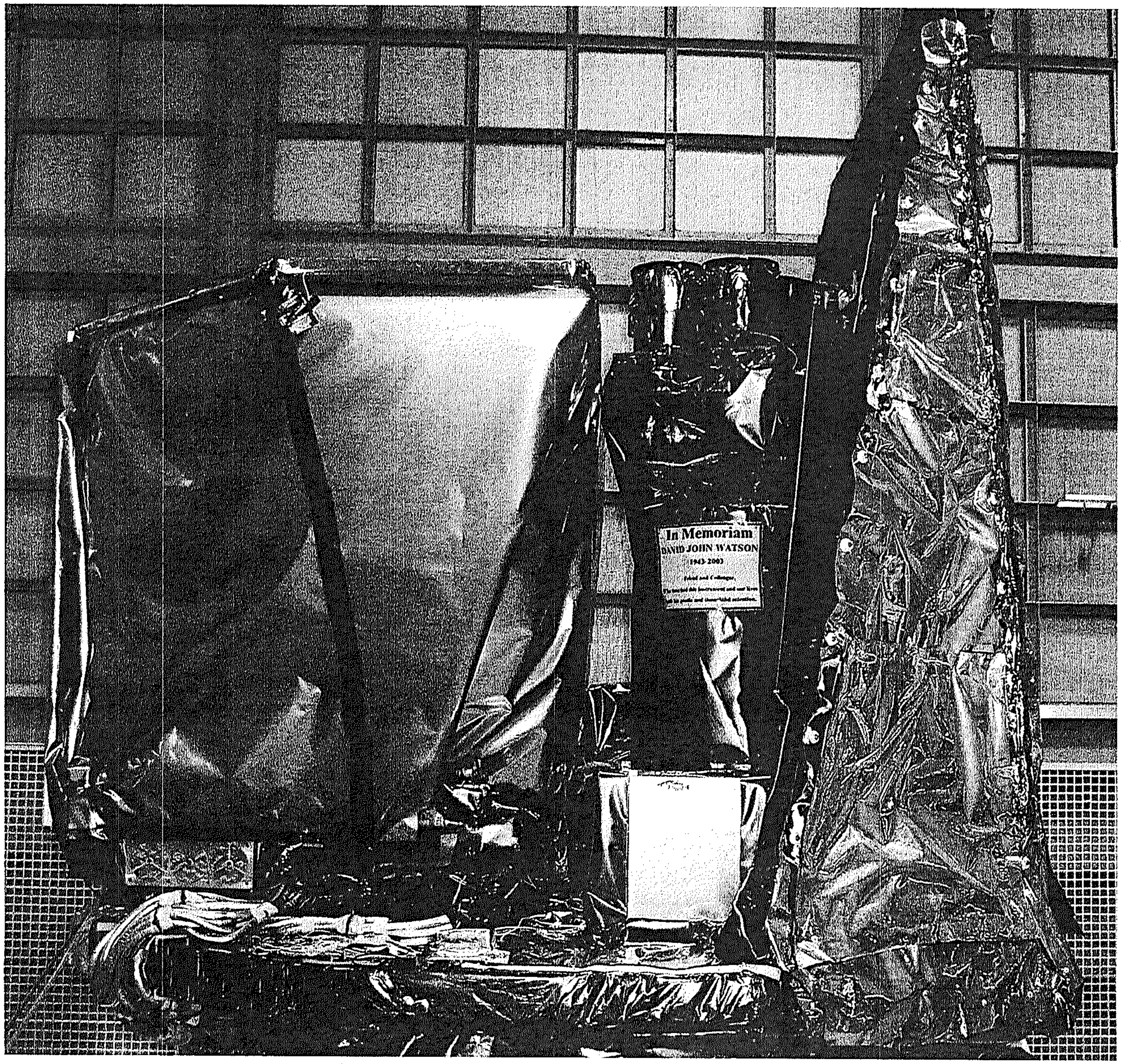
- Burst Alert Telescope (BAT)
  - New CdZnTe detectors
  - Detect ~100 GRBs per year depending on logN-logS
  - Most sensitive gamma-ray imager ever
- X-Ray Telescope (XRT)
  - Arcsecond GRB positions
  - CCD spectroscopy
- UV/Optical Telescope (UVOT)
  - Sub-arcsec imaging
  - Grism spectroscopy
  - 24th mag sensitivity (1000 sec)
  - Finding chart for other observers
- Spacecraft
  - Autonomous re-pointing, 20 - 75 sec
  - Onboard and ground triggers

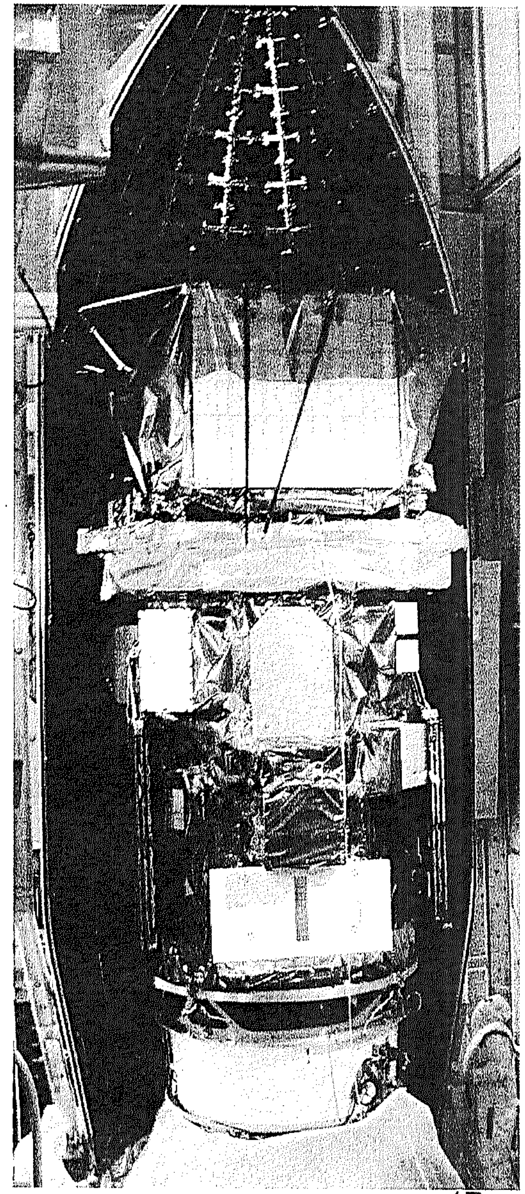
Swift Spacecraft & Instruments



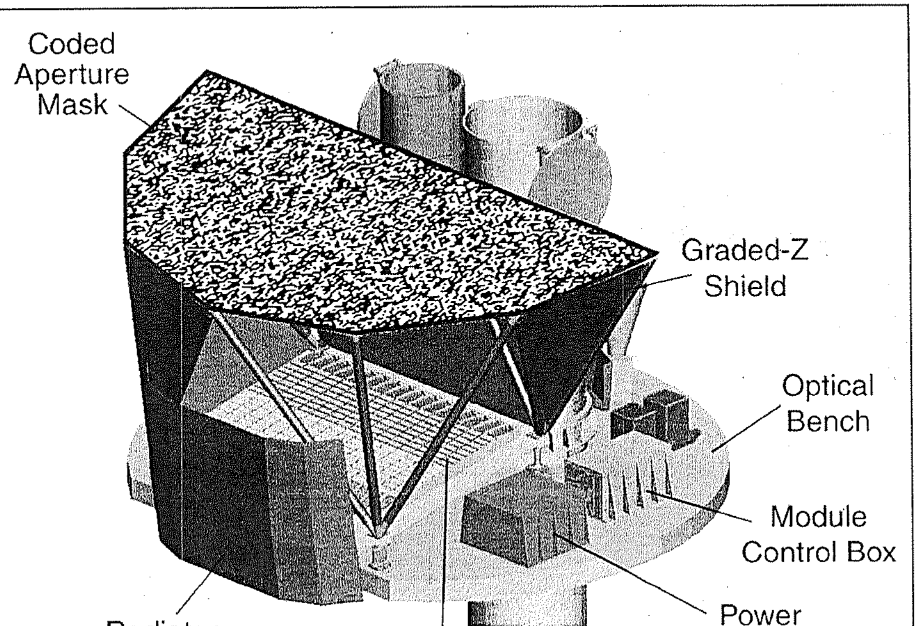


Swift Instruments and Launch Vehicle

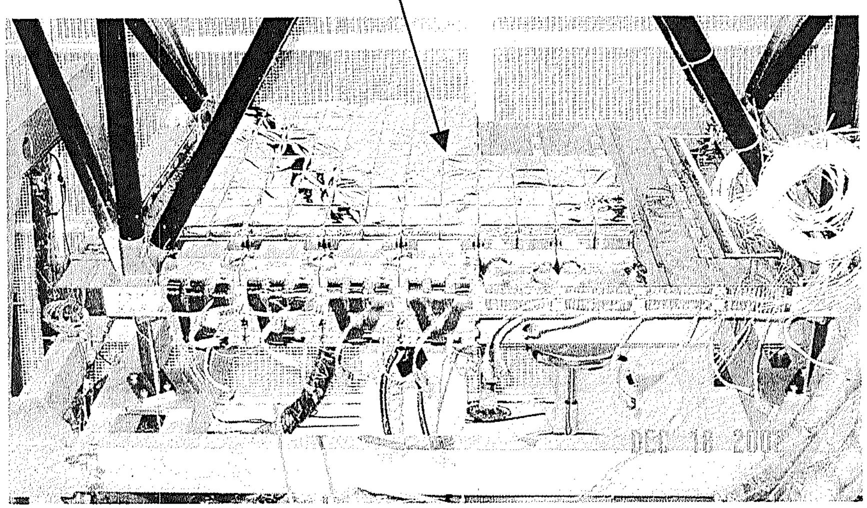




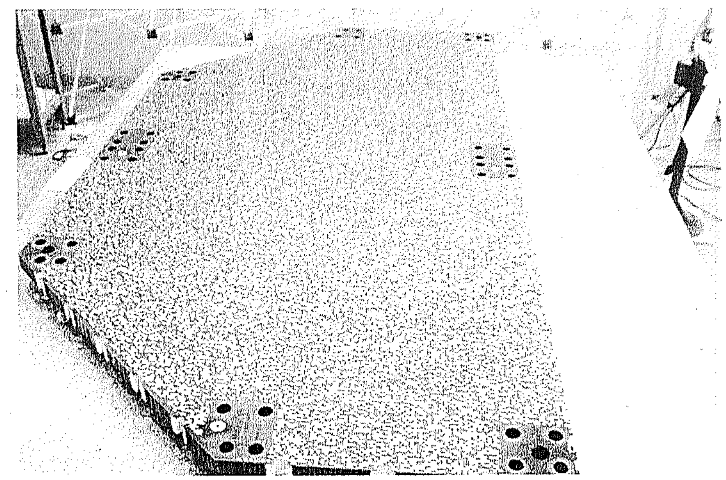
Burst Alert Telescope (BAT)



BAT Detector Array



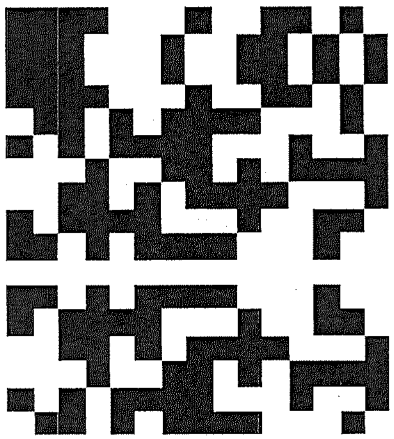
Coded Aperture Mask



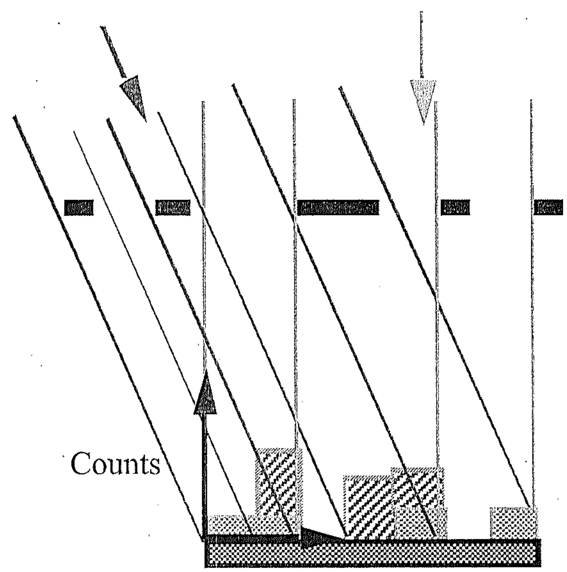
Telescope	Coded Aperture
Aperture	2.7 m^2
Energy Range	15 - 150 keV (12-300 keV)
Energy Resolution	7 keV (5 keV)
Location Resolution	1-4 arcmin (1 - 4')
Sensitivity	1×10^{-8} erg sec^{-1} cm^{-2}
Field of View	1.4 steradian
PSF	17 arcmin
Detector	32 000 CZT
Mode	Photon-Counting (Autonomous)

Coded-Aperture Imaging

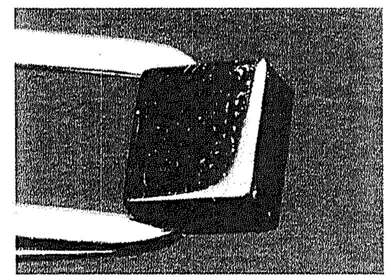
Coded Aperture
Mask Pattern



5 mm square Pb tiles



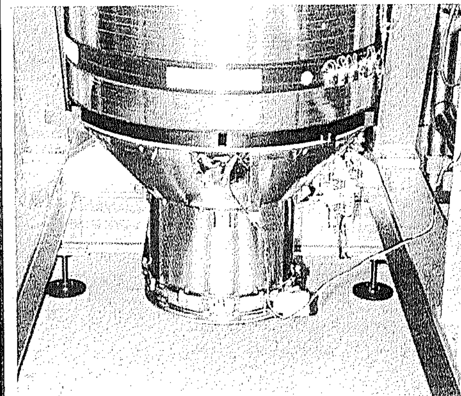
4 mm square CZT

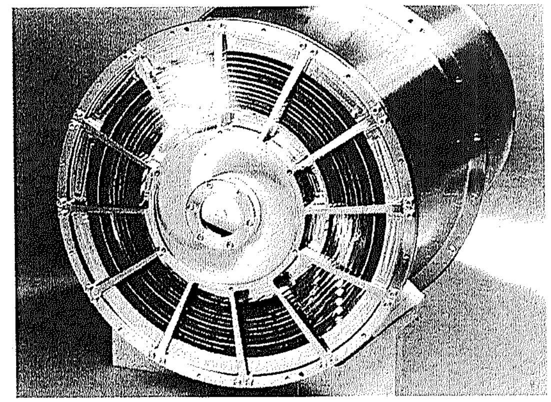


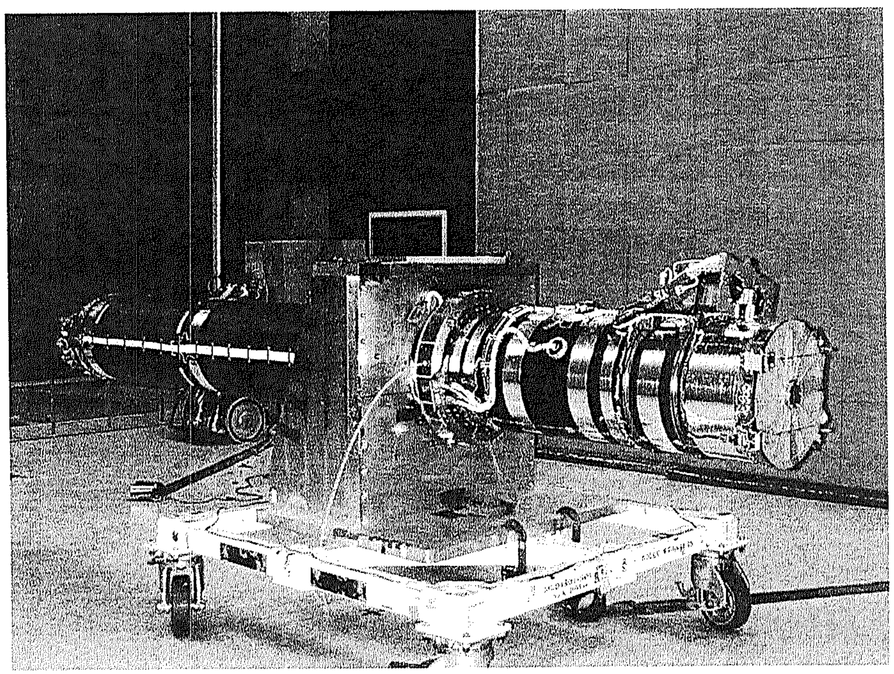
- Source Photons "Encoded" by Partially Blocked Aperture
- Can be Decoded in Data Analysis to Determine Source Position
- Missing Pixels = Graceful Degradation in Sensitivity

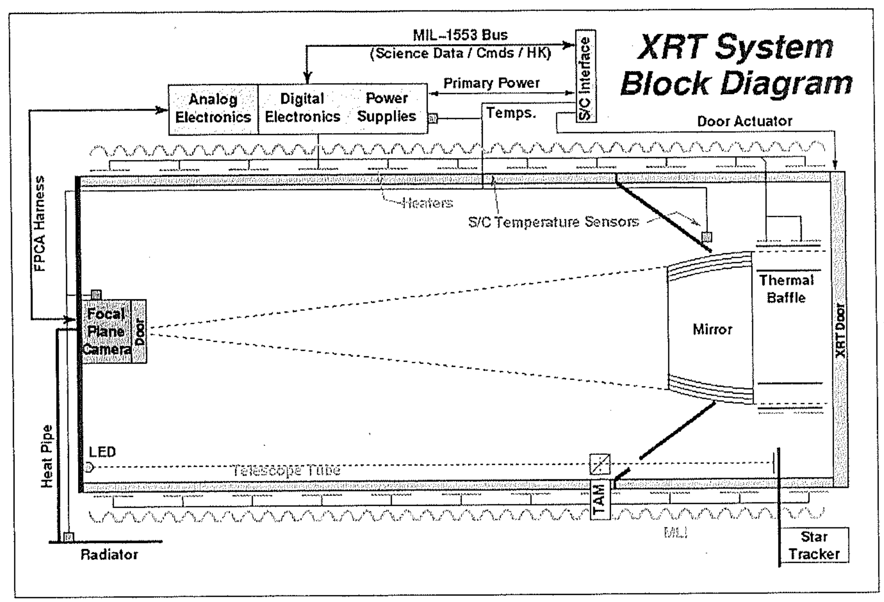
The X-Ray Telescope

Telescope	Wolter I
Energy Range	0.2-10 keV
Aperture	0.51 m
Sensitivity	1×10^{-14} erg sec^{-1} cm^{-2} in 10 000 s
Field of View	23.6 x23.6 $arcmin^2$
PSF	18 arcsec FWHM @ 1.5 keV
Detector	e2v CCD-22
Mode	Autonomous



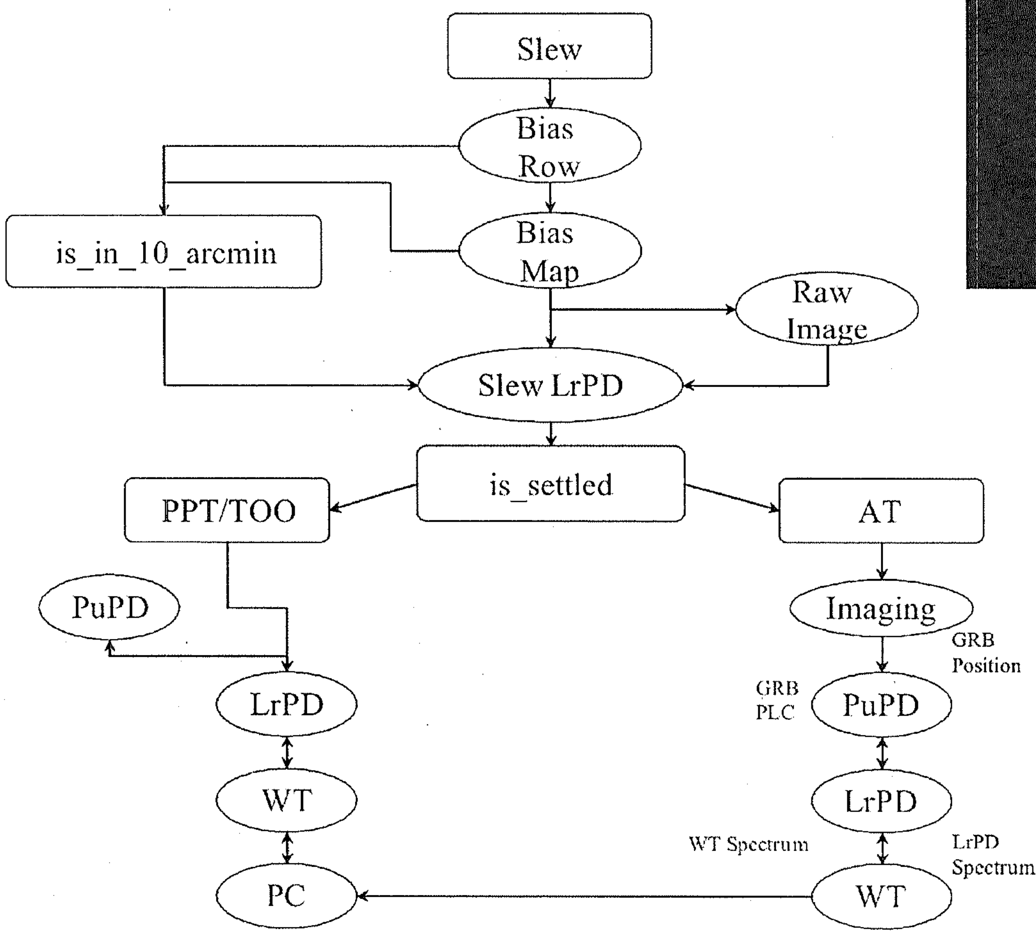


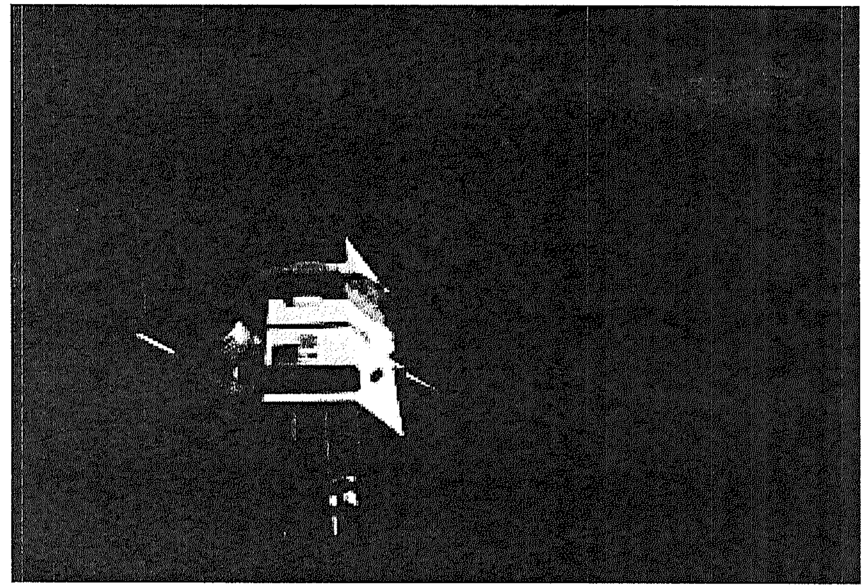


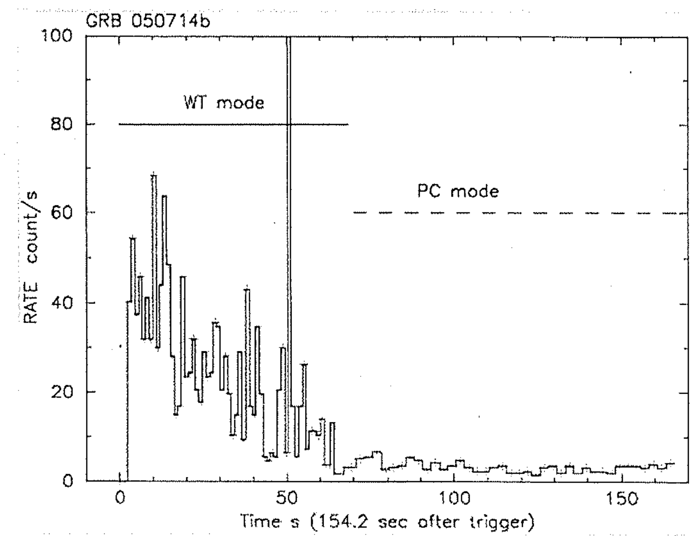


Autonomous Operation of the XRT

Image	Centroiding, 0.1 or 2.5 sec timing
Photodiode	10 μs timing, limited spectral capability
Windowed Timing	2.2 ms timing, med. res spectrum, 1-d pos.
Photon Counting	2.56 sec timing, med. res.spectrum, 2-d pos.

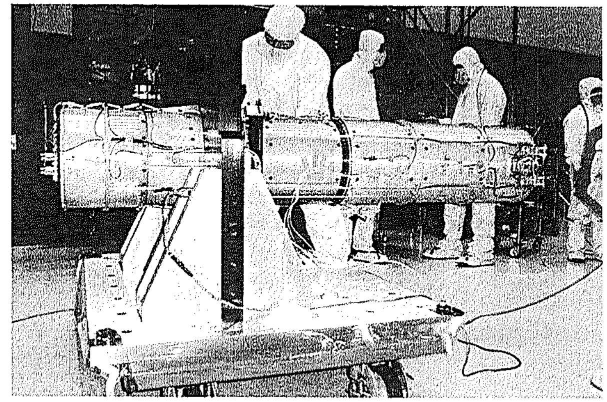


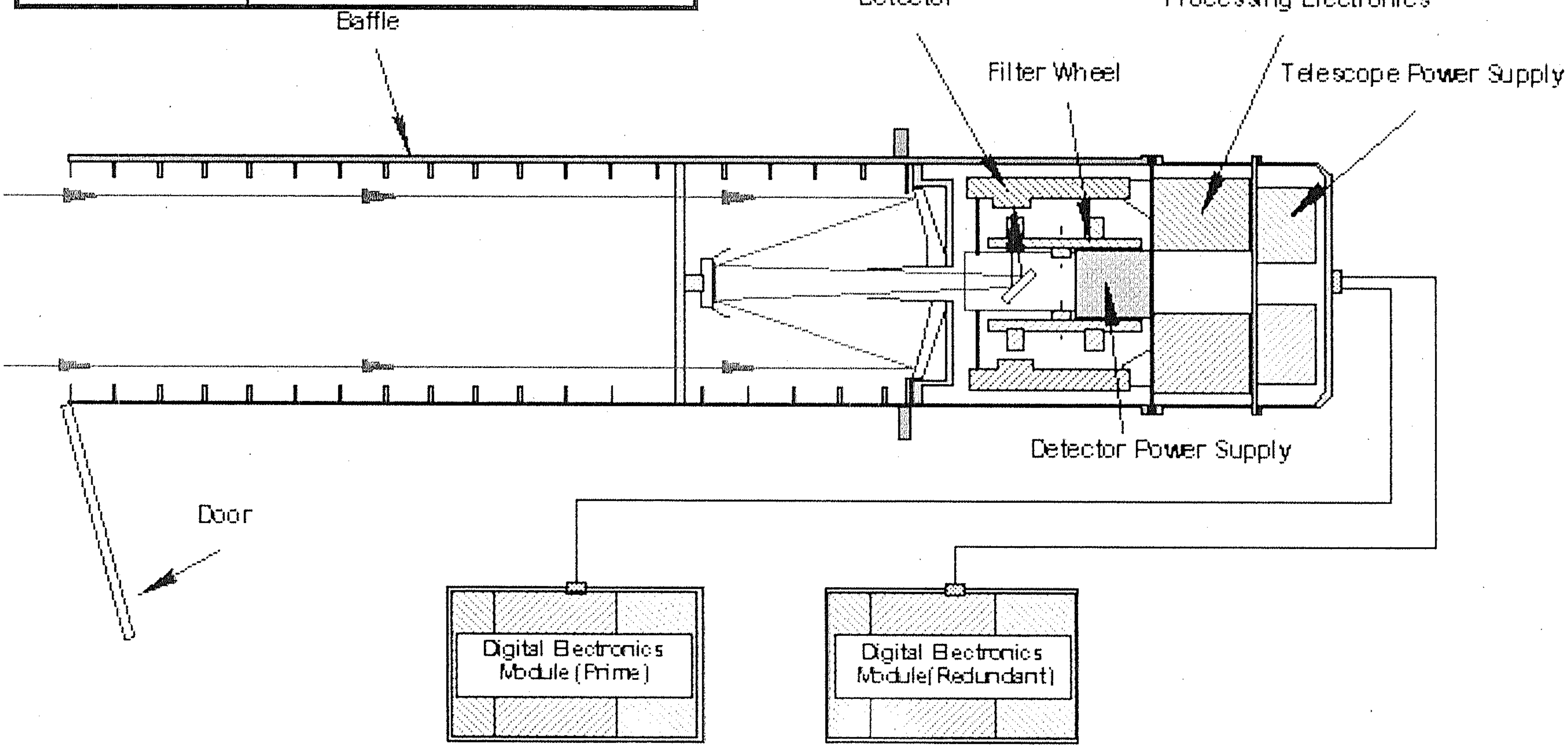




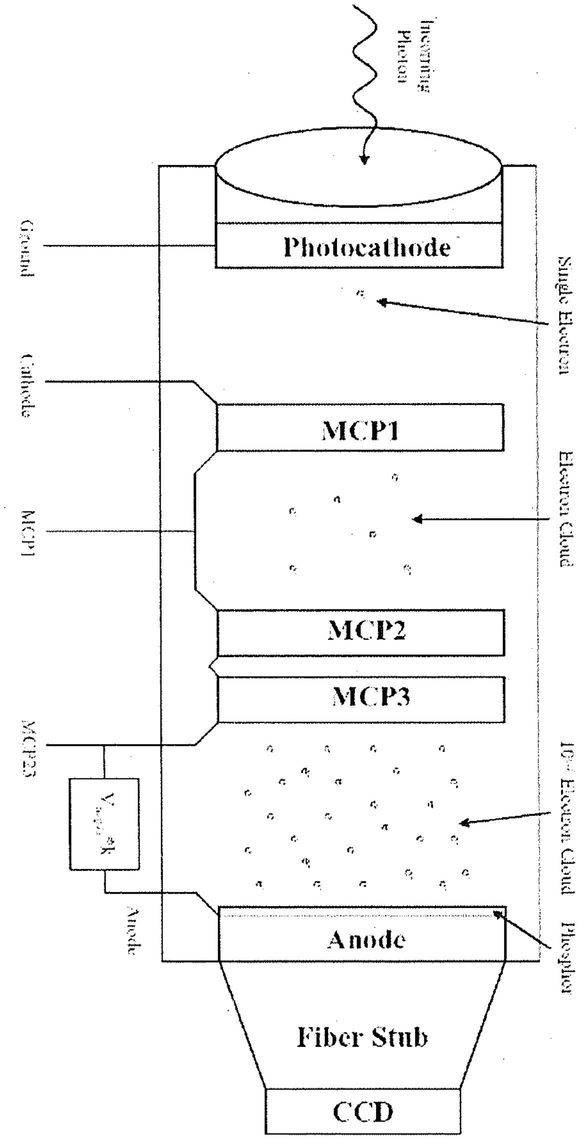
The UV/Optical Telescope

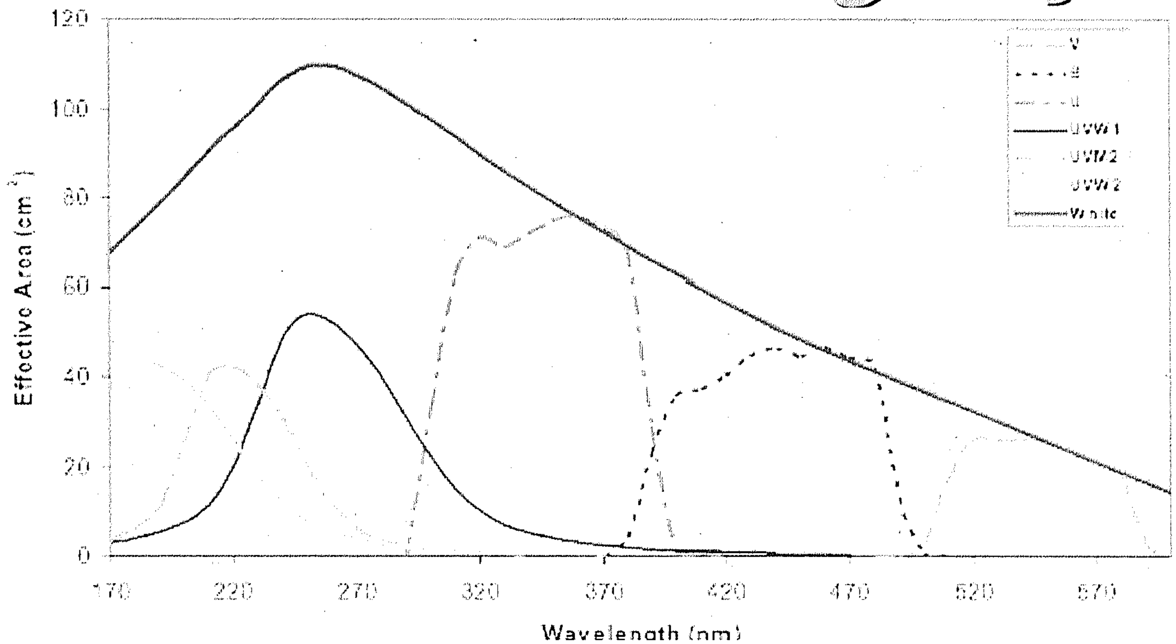
Telescope	Modified Ritchey-Chrètien
Aperture	30 cm diameter
Wavelength	170-600 nm
Sensitivity	m_B=24.0 in white light in 1000 s
Field of View	17 x17 arcmin^2
PSF	0.9 arcsec FWHM @ 350 nm
Detector	MCP Intensified CCD
Mode	Photon Counting

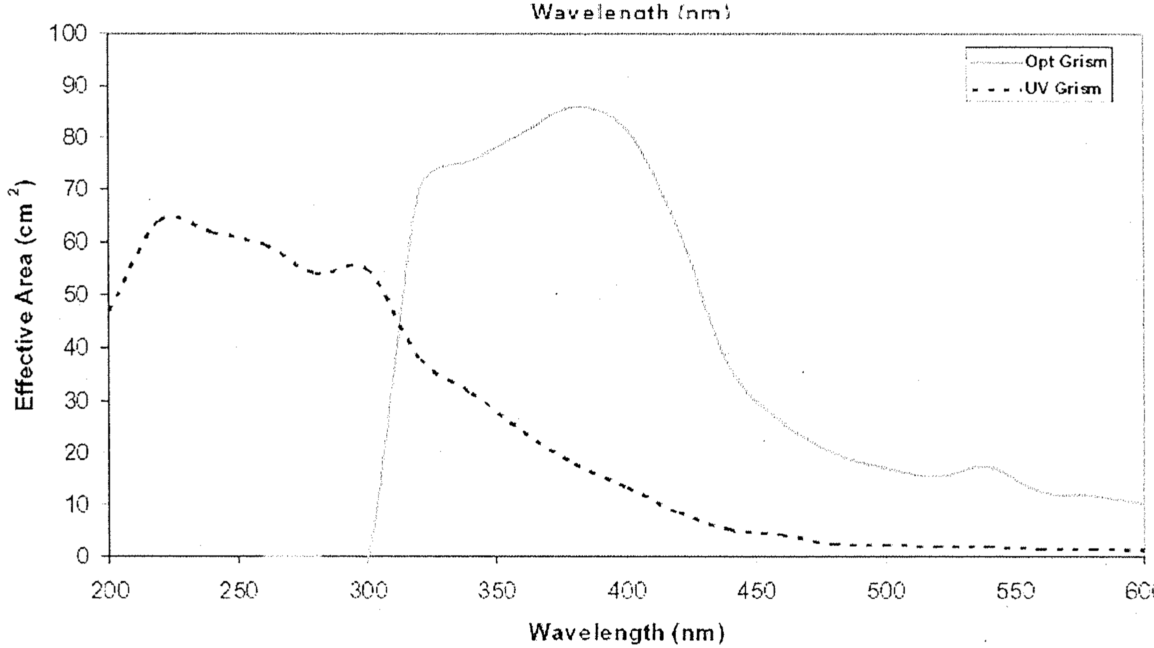




The UV/Optical Telescope





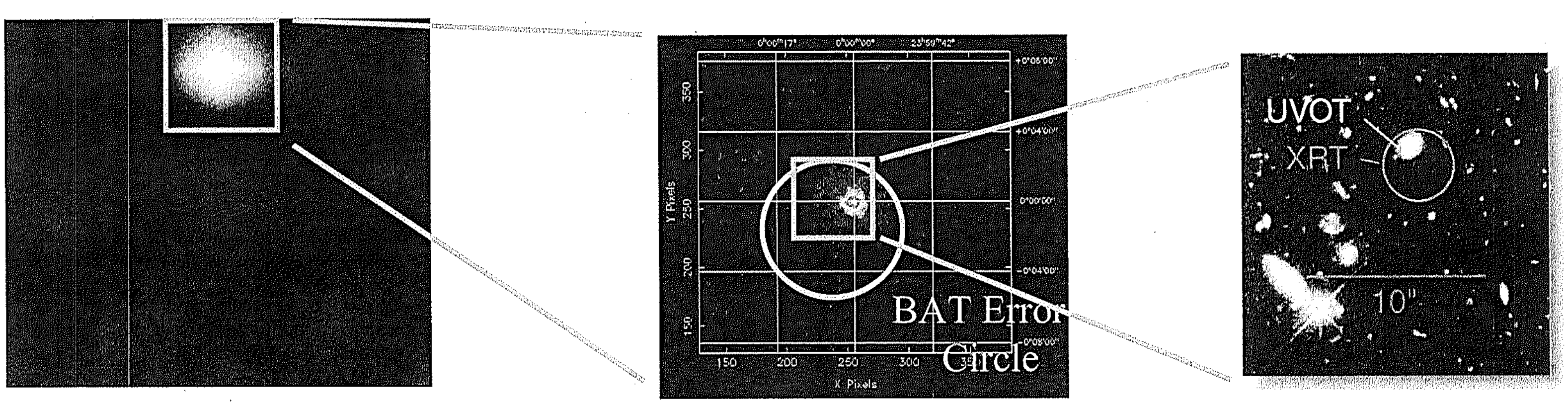


10.8 ms readout of 17 x17 arcmin FoV
Onboard centroiding provides photon positions

Observing Scenario

1. Burst Alert Telescope triggers on GRB, calculates position to ~ 1 arcmin
2. Spacecraft autonomously slews to GRB position in 20-70 seconds
3. X-ray Telescope determines position to ~ 3 arcseconds
4. UV/Optical Telescope images field, transmits finding chart to ground

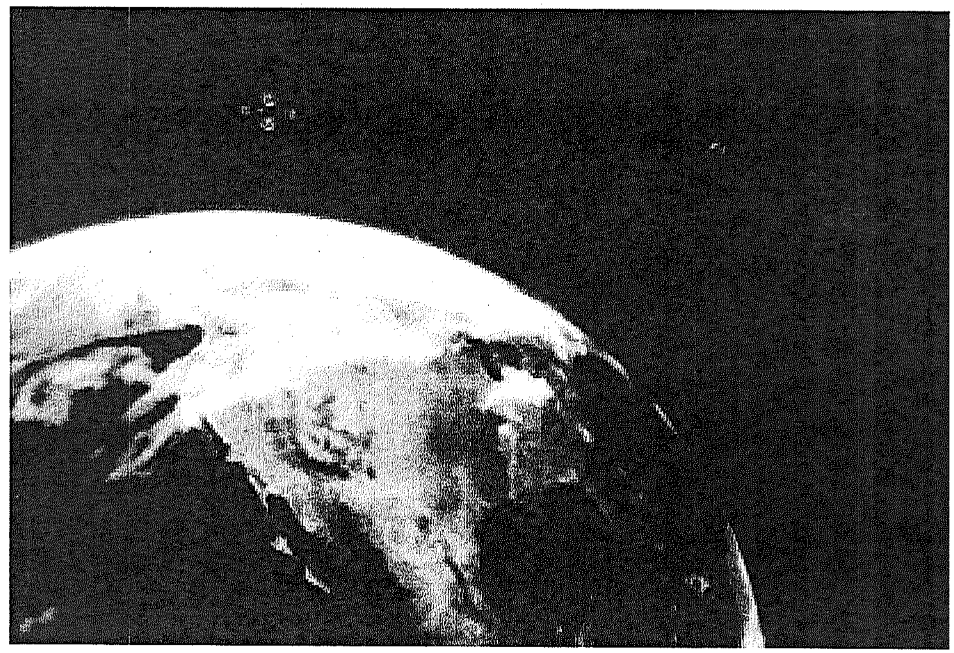
BAT Burst Image | XRT Image | UVOT Image



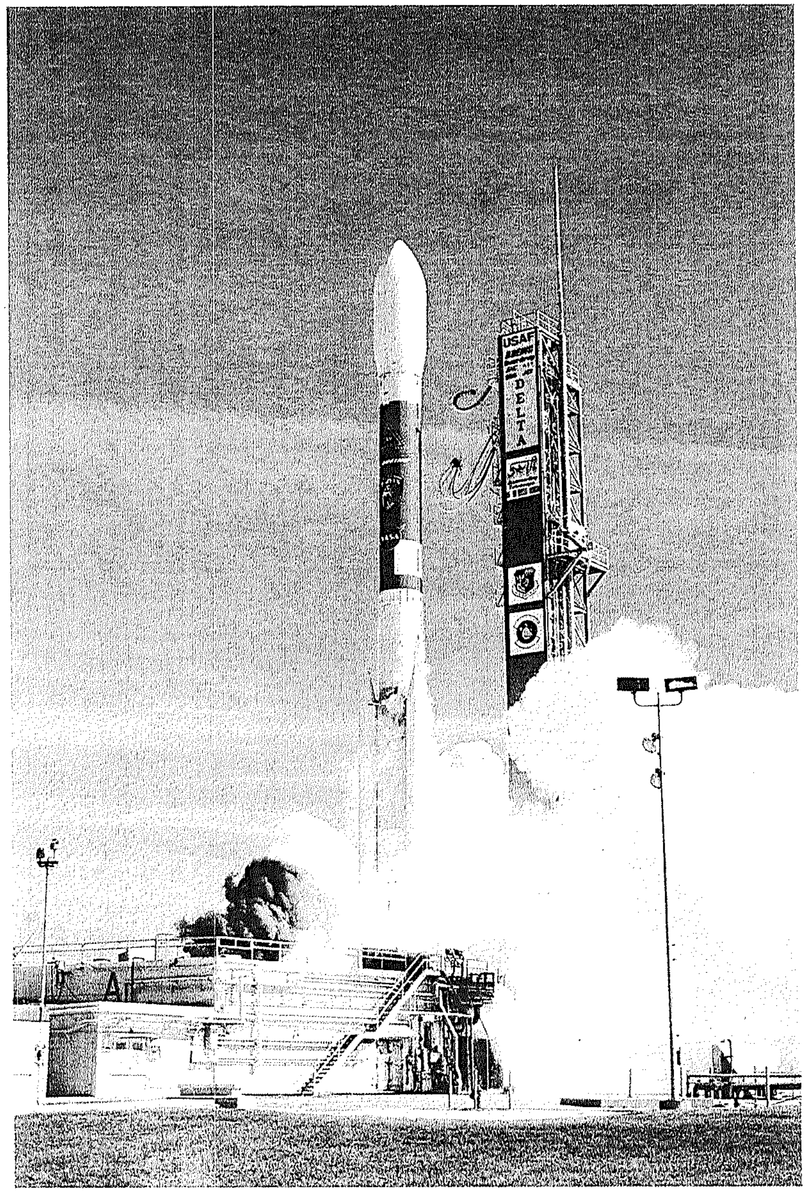
T~10 sec | T~100 sec | T~300 sec

Data transmission

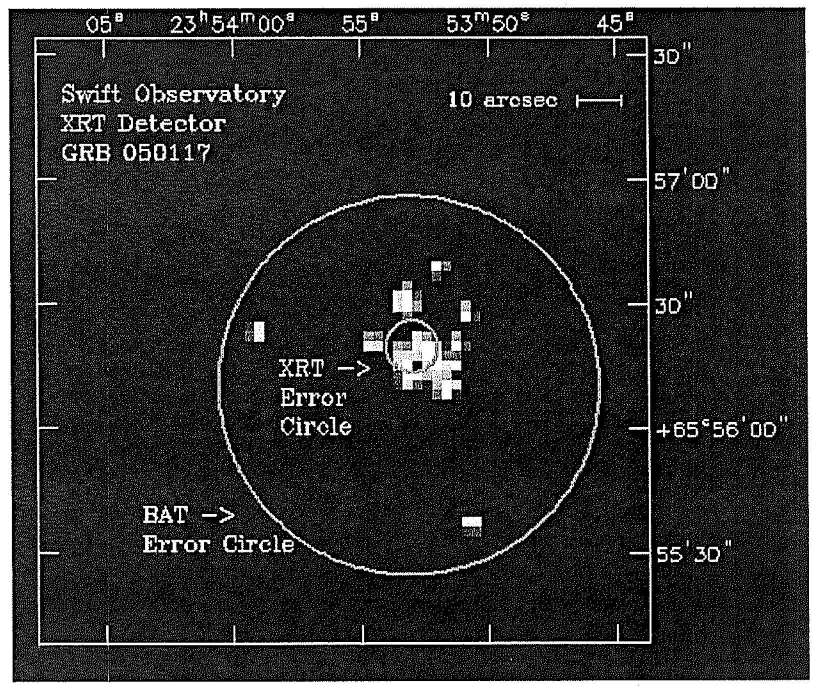
- Rapid dissemination of data to the world via TDRSS
  - Positions
  - Quicklook Lightcurves
  - Raw Images
  - Quicklook spectra
- Ground pass over Malindi to telemeter data from the solid state recorder on the spacecraft for ground processing
  - Event files
  - Processed lightcurves
  - Refined positions
  - Spectral characteristics



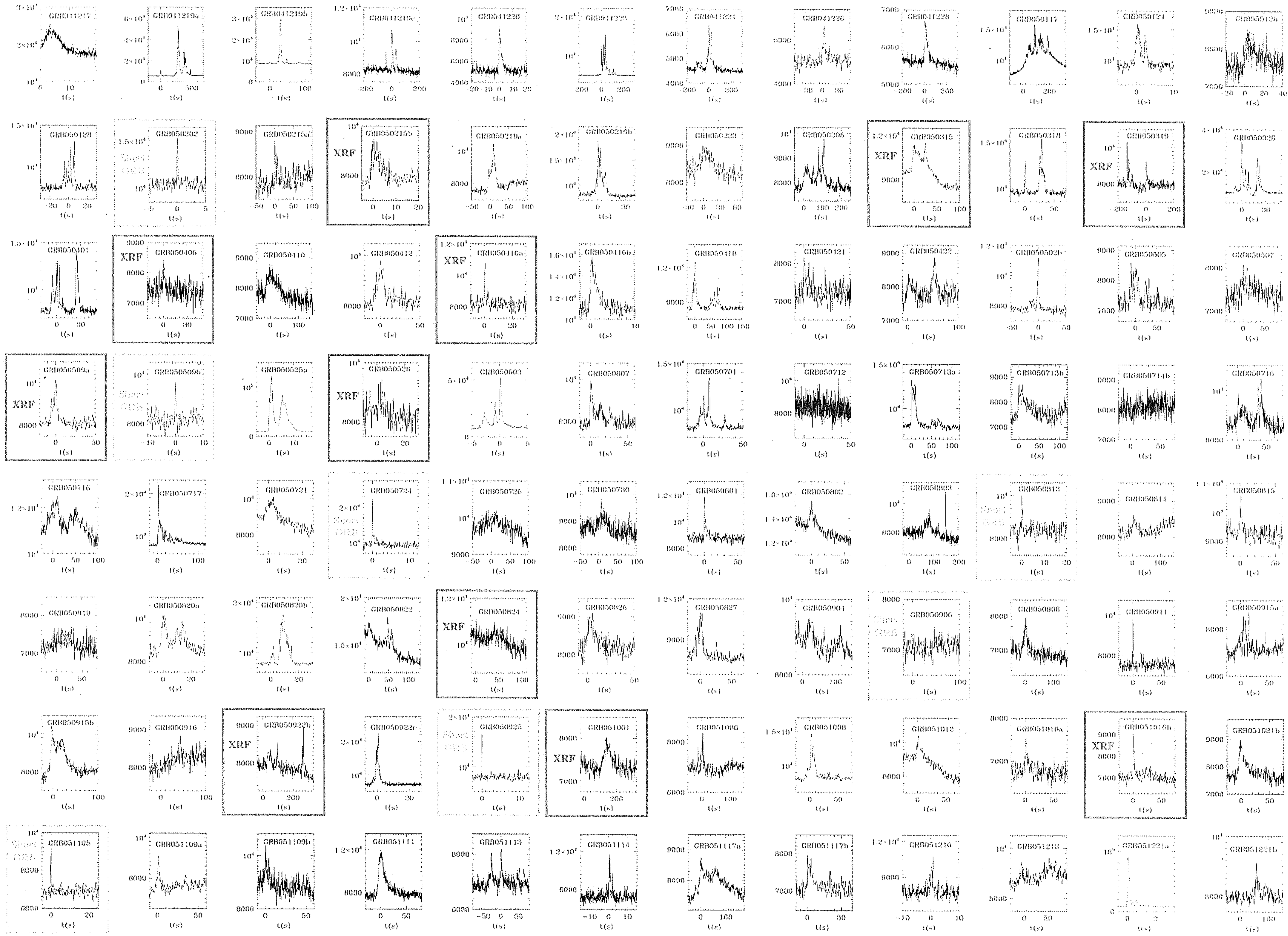
The Swift Observatory

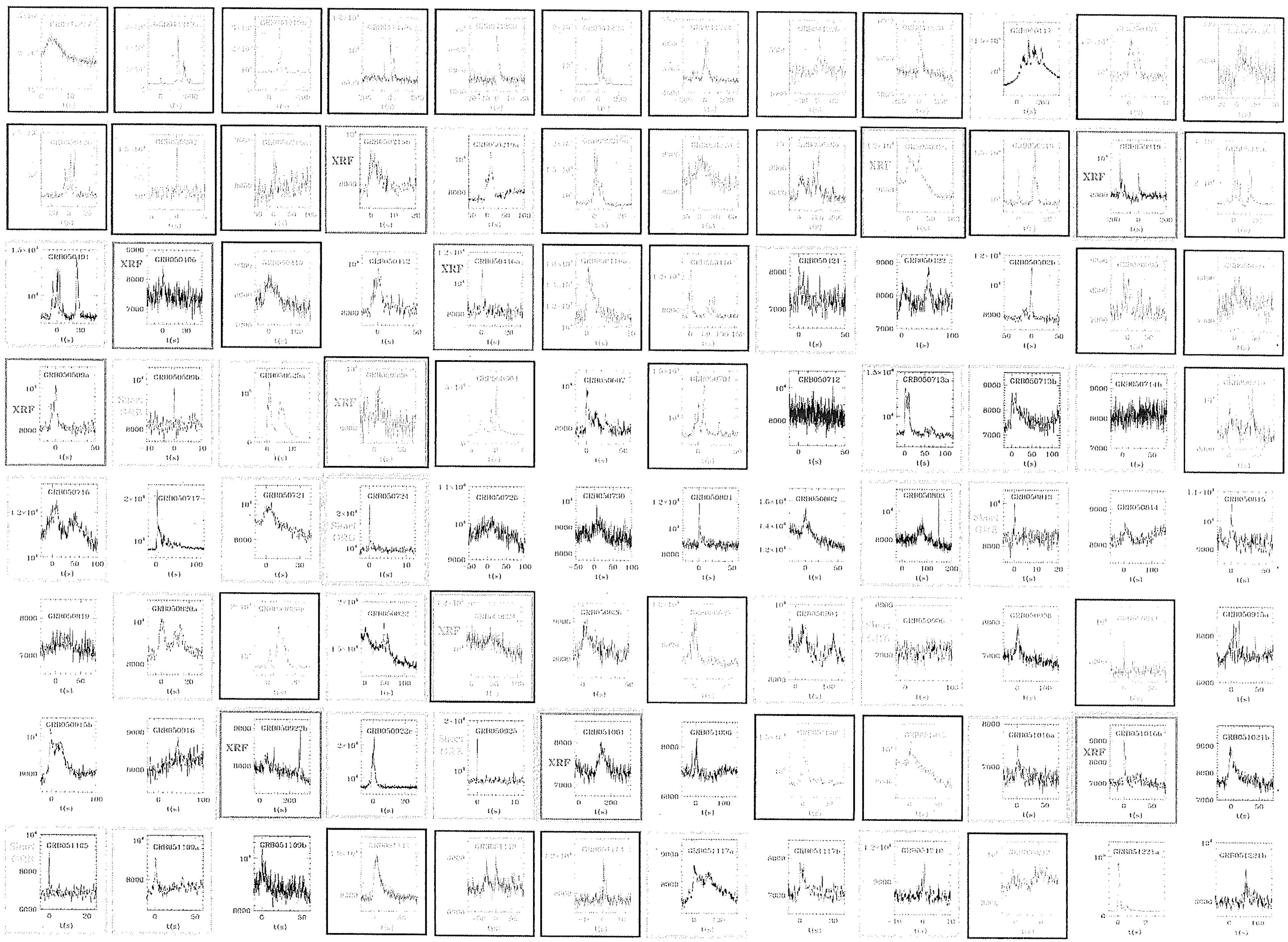


- Launched: 20 November 2004
- BAT First Light: 3 December 2004
- XRT First Light: 11 December 2004



- First BAT Burst: 17 December 2004
- First XRT Afterglow: 23 December 2004
- UVOT First Light: 12 January 2005
- Data public since 5 April 2005





GRB050401
GRB050406
GRB050412
GRB050416a
GRB050421
GRB050422
GRB050502b
GRB050509a
GRB050509b
GRB050525a
GRB050607
GRB050712
GRB050713a
GRB050713b
GRB050714b
GRB050716
GRB050717
GRB050721
GRB050724
GRB050726
GRB050730
GRB050801
GRB050802
GRB050803
GRB050813
GRB050814
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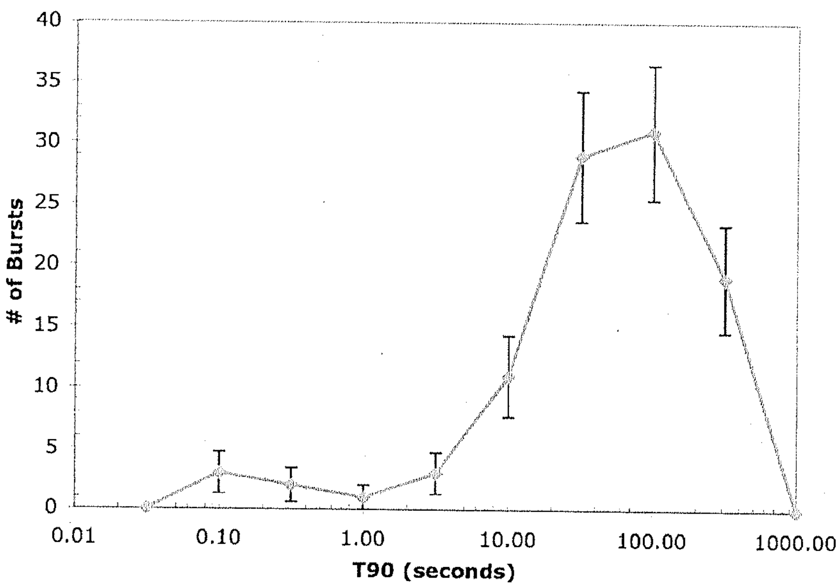
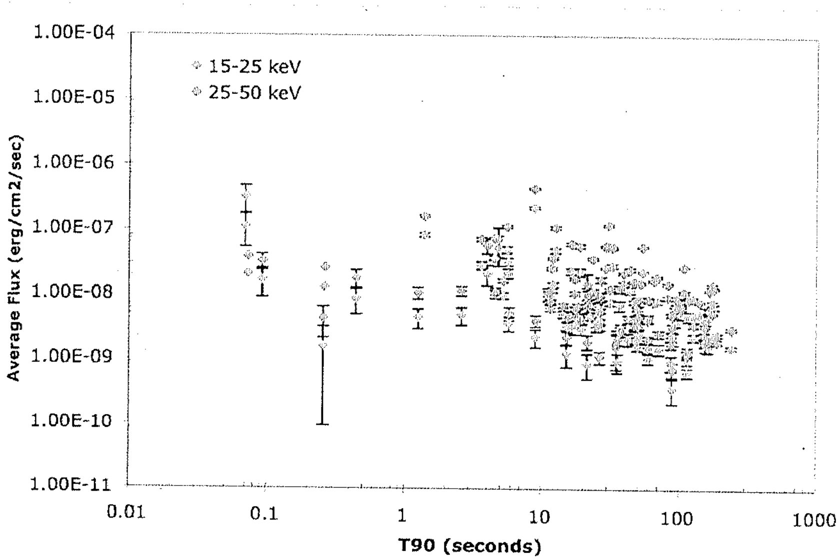
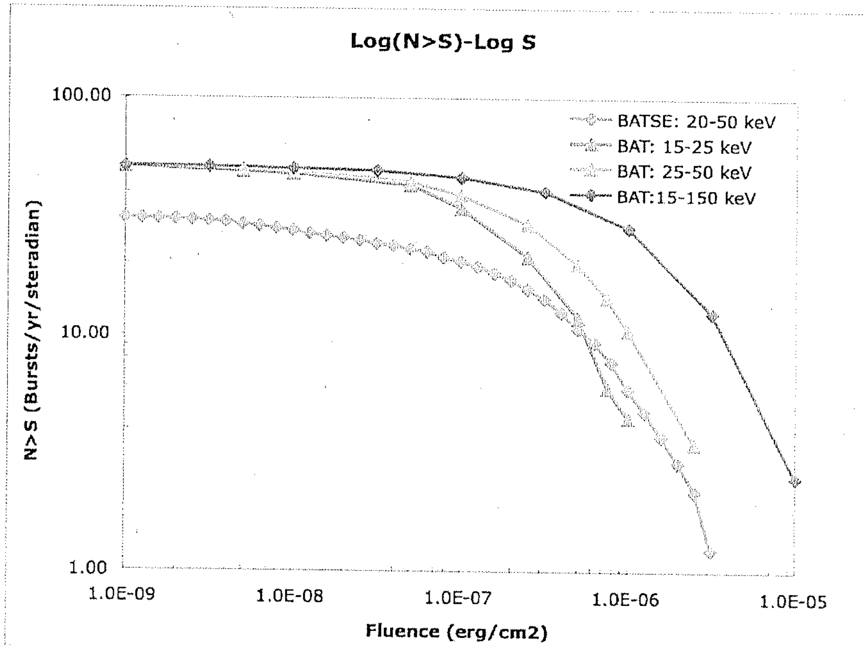
GRB050915a
GRB050915b
GRB050916
GRB050922b
GRB050922c
GRB050925
GRB051001
GRB051006
GRB051016a
GRB051016b
GRB051021b
GRB051105
GRB051109a
GRB051109b
GRB051117a
GRB051117b
GRB051221a
GRB051221b
XRF
Short GRB
t(s)

BAT Bursts



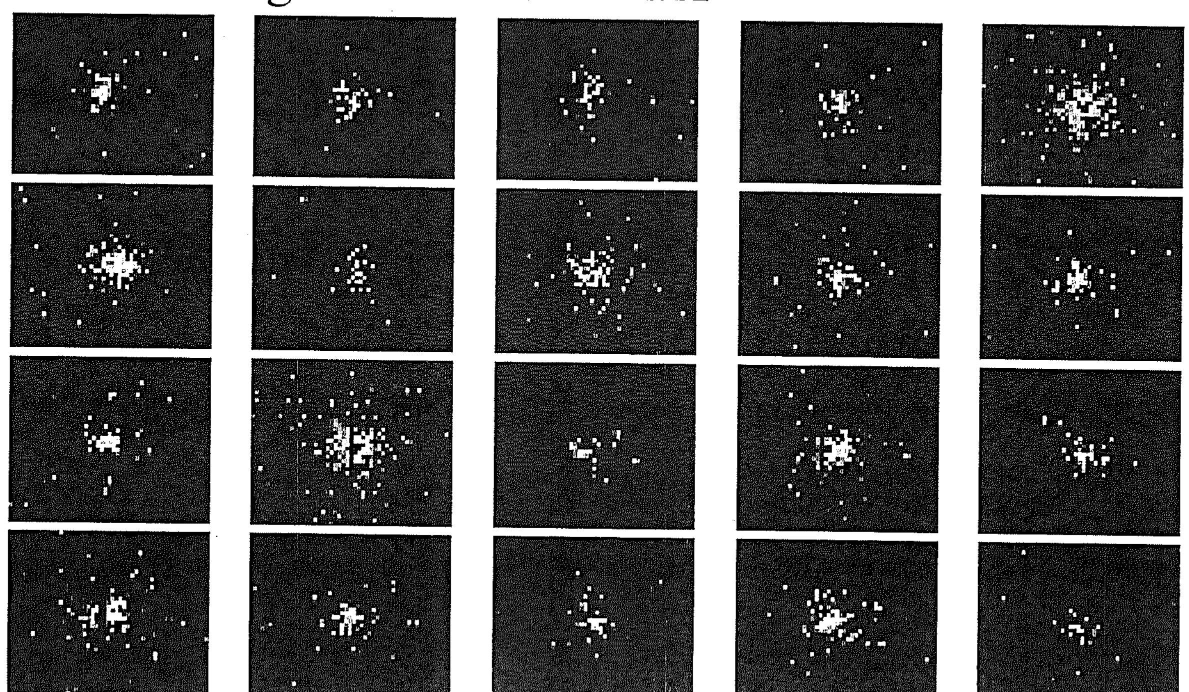
- Distributions from 104 bursts between 17 December 2004 - 11 January 2006
- Bi-modal the same as BATSE
- LogN-LogS shows higher sensitivity



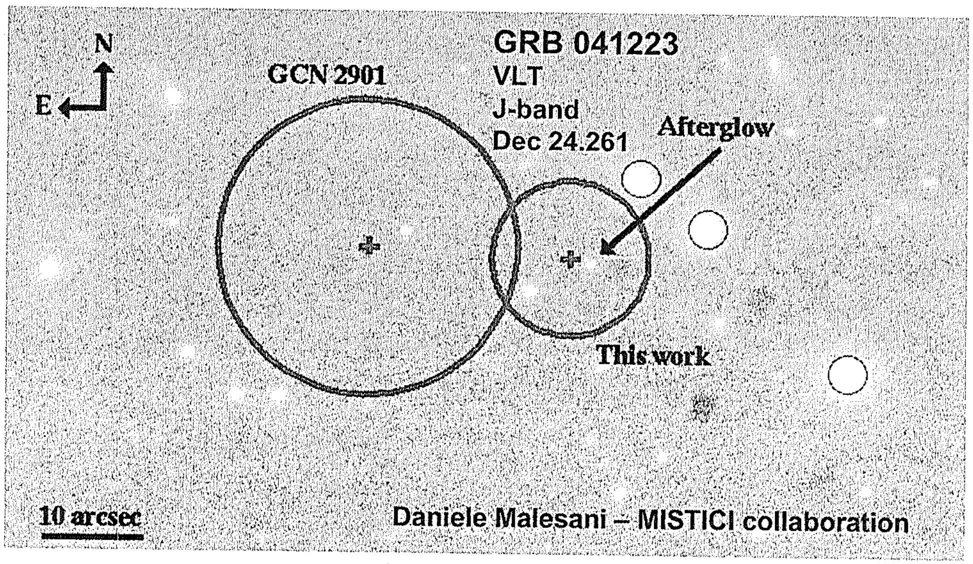


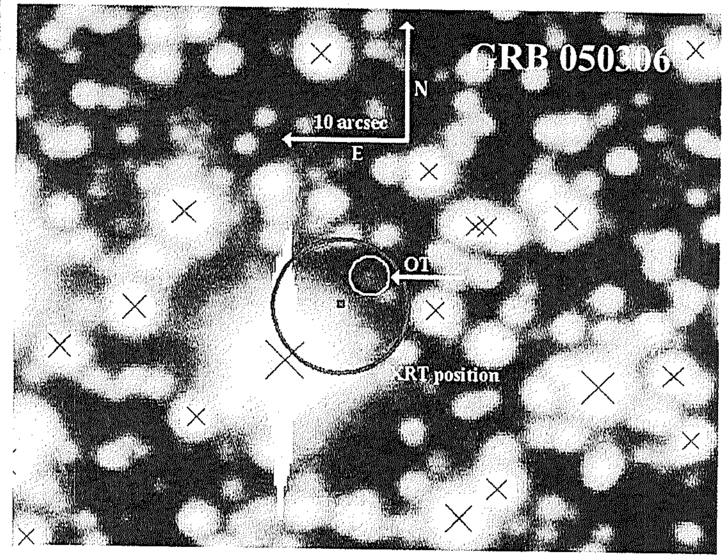
XRT Detections of BAT GRBs

- Detected 103/109 with XRT (observed @ $T < 250$ ks)
  - Observed during prompt emission: 050117, 050717, 050820a, 050904, 060124, 060218
  - 72% Swift detections were prompt observations (< 350 s)
    - 82% have fast decline or a flare within first ~5 minutes
  - 32 have redshift measurements:
    - Average redshift: 2.2 (compared with 1.2 pre-swift bursts)
    - Highest redshift: 6.29 (highest GRB redshift on record)
- Detected 5/7 HETE bursts with XRT
- Detected 6/13 Integral bursts with XRT

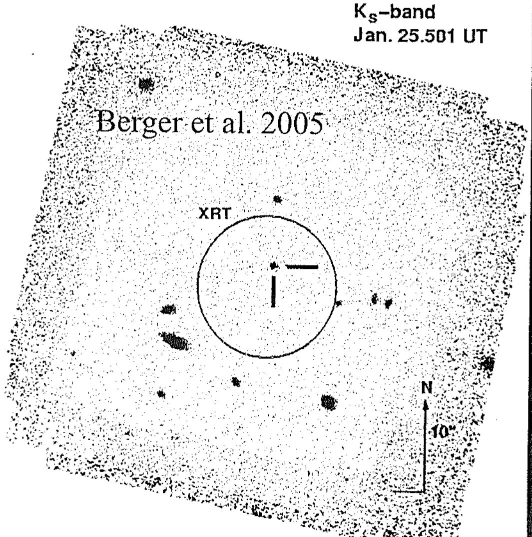


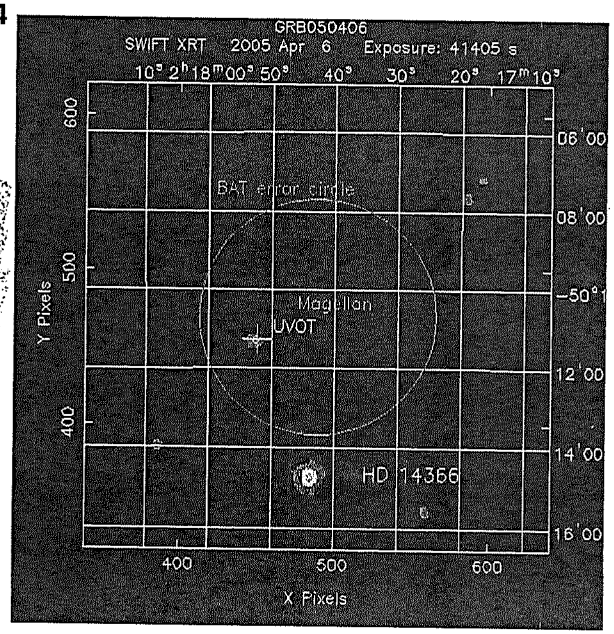
XRT Positional Accuracy

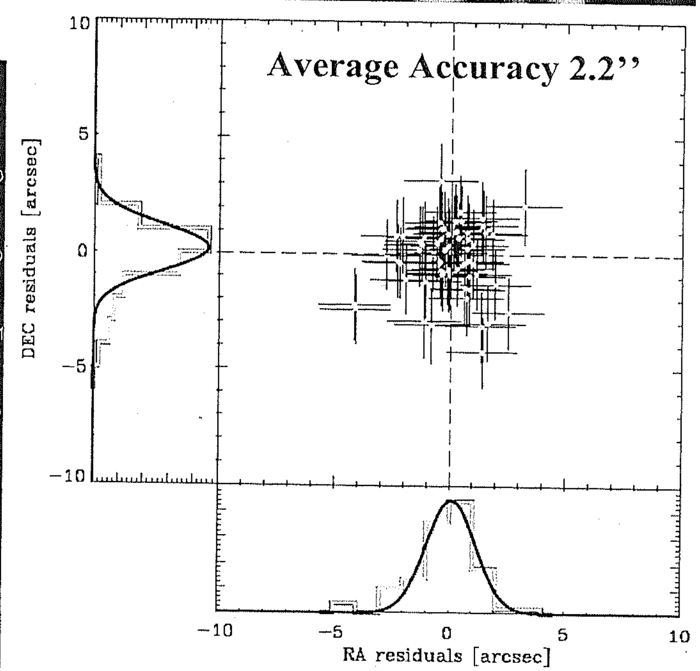




GRB 050124
Keck/NIRC
K_s–band
Jan. 25.501 UT

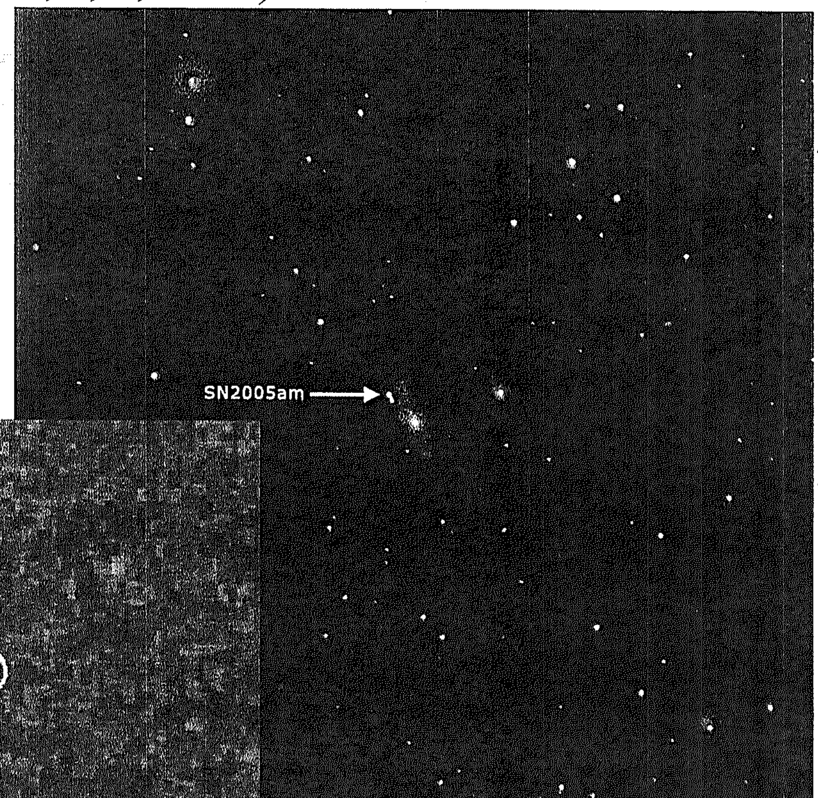


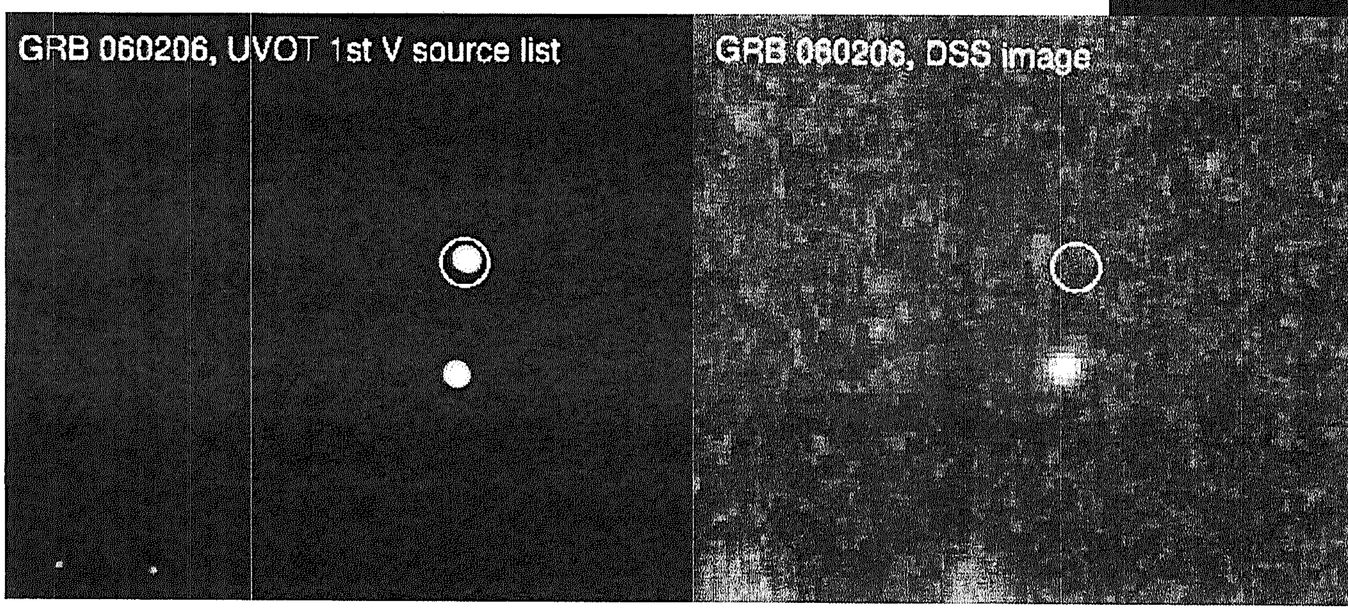




UVOT Detections of BAT GRBs

- Detected 26/55 with UVOT
  - UVOT upper limits are quite faint and very early for many bursts
  - More ground-based detections (typically R, I, J, or K)
    - High z
      - Evidence in some cases
    - Dust extinction
      - Evidence supporting this for some bursts
    - Intrinsically Dark
      - Magnetic suppression?





GRB 050318: the first UVOT afterglow

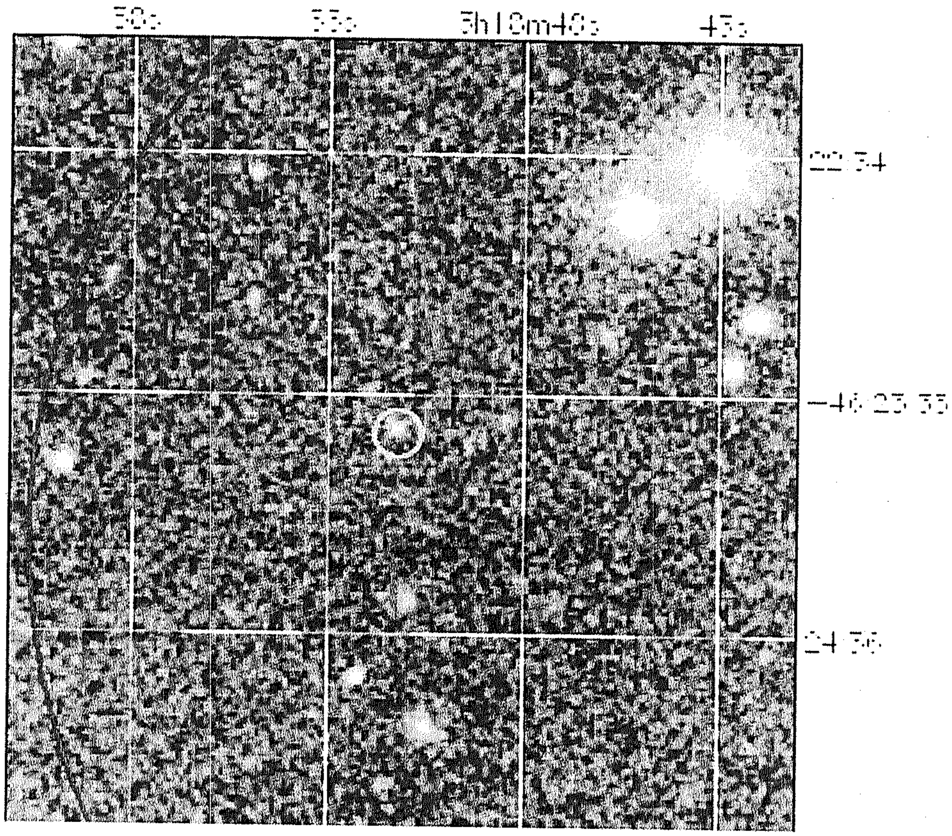
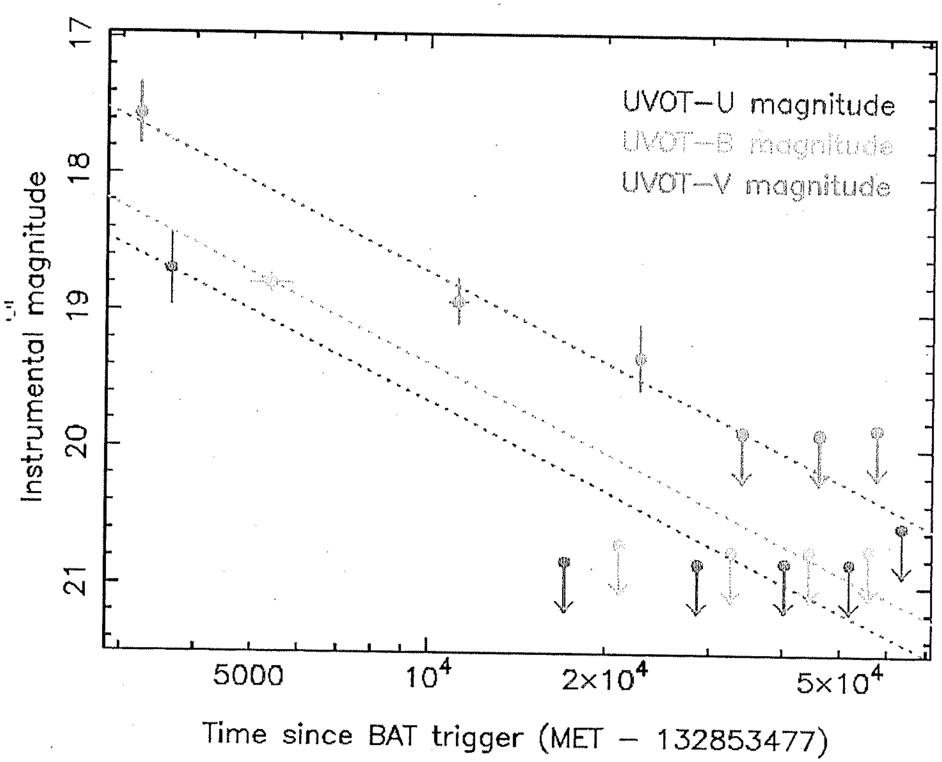
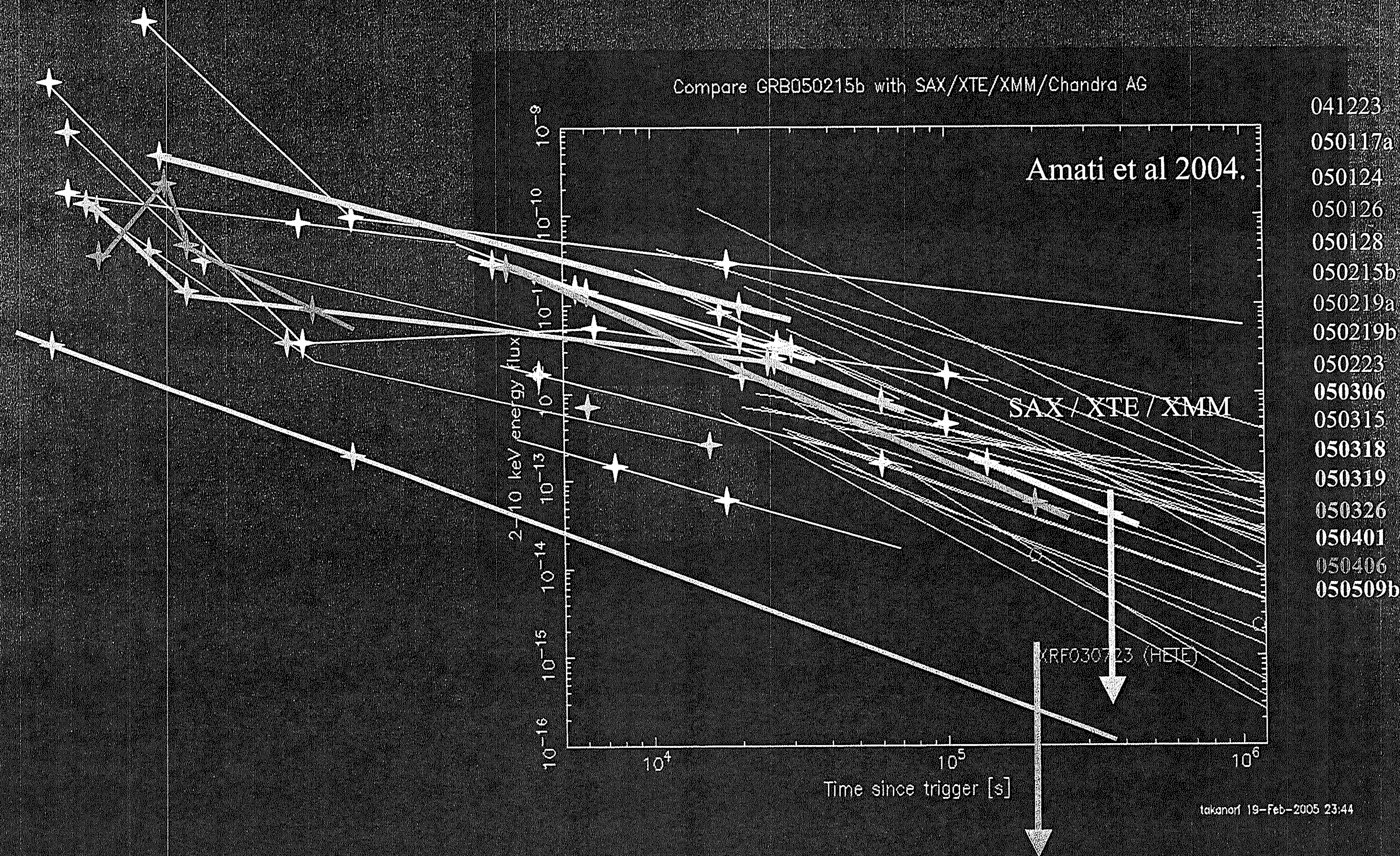
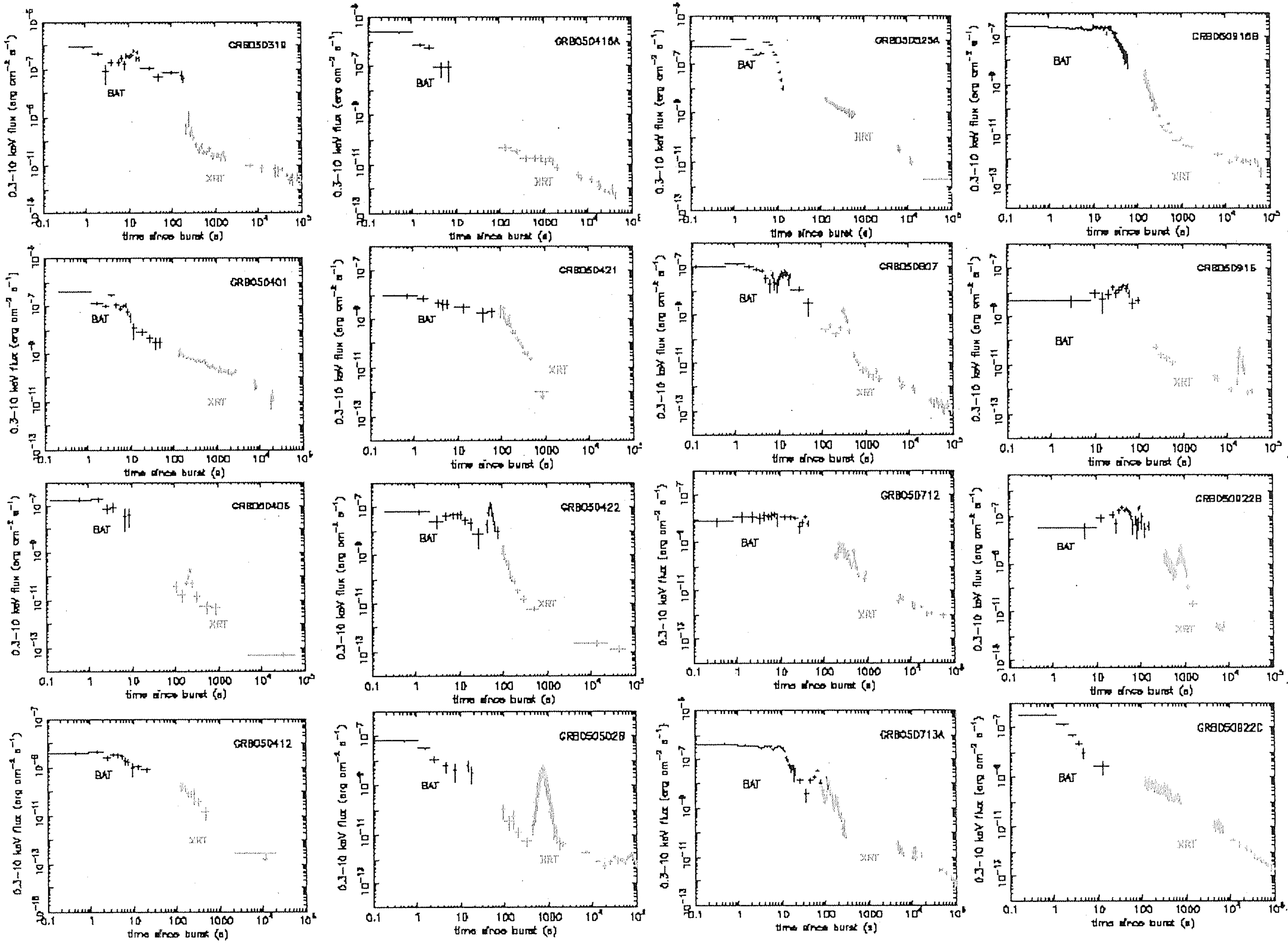


FIG. 1.— Stacked UVOT-V filter image of the field with the transient source at RA = $03^h\ 18^m\ 51^s.15$, Dec = $-46°\ 23'\ 43''.7$ (J2000) and a 3′ BAT error circle and 6″ XRT error circle overlaid. Total exposure time for the stacked image is 3,732s.



XRT Afterglow Summary



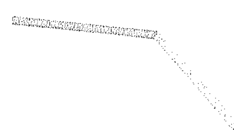


GRB050416A
GRB050401
GRB050421
GRB050807
GRB050915
GRB050406
GRB050422
GRB050712
GRB050822B
GRB050412
GRB050502B
GRB050713A
GRB050822C
BAT
XRT
0.3–10 keV flux (erg cm^{-2} s^{-1})
time since burst (s)

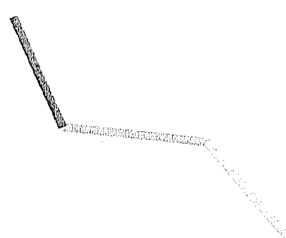
XRT Afterglow Types

From the XRT prompt observations, we see that there are at least 3 shapes of afterglow lightcurves:

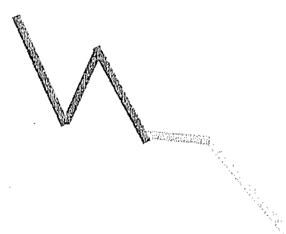
- Type A



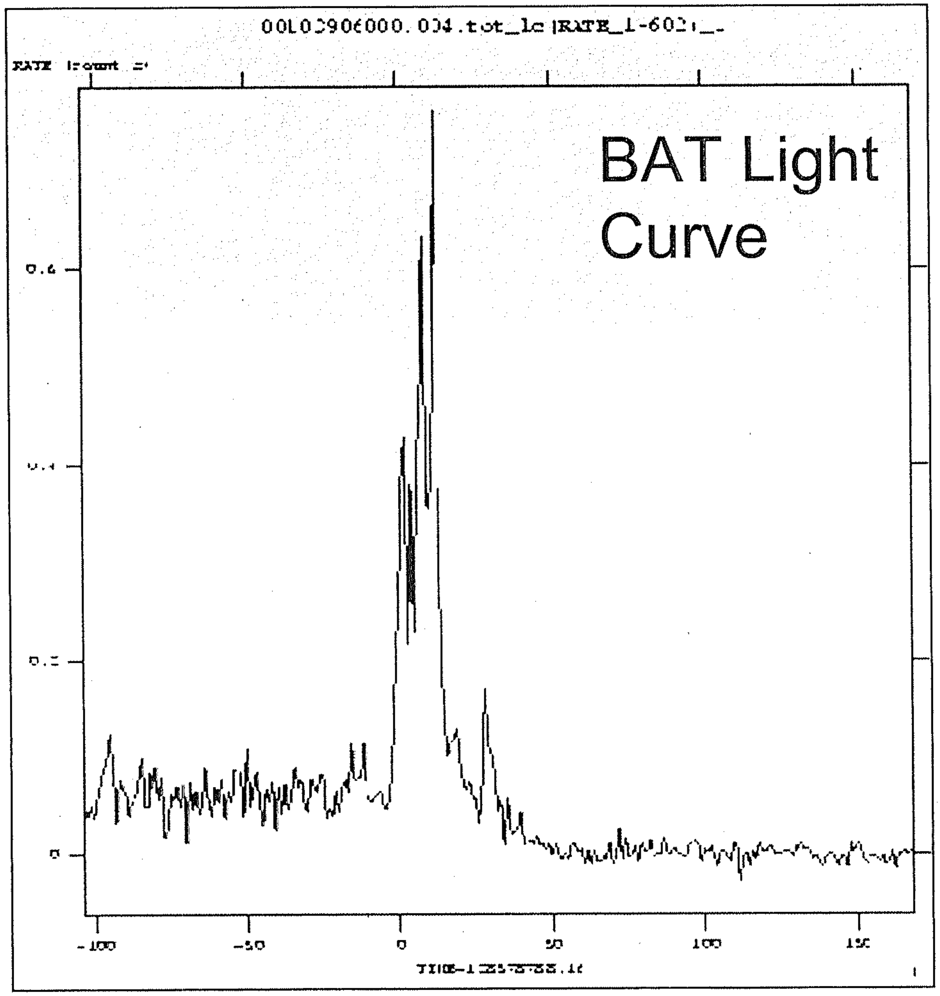
- Type B



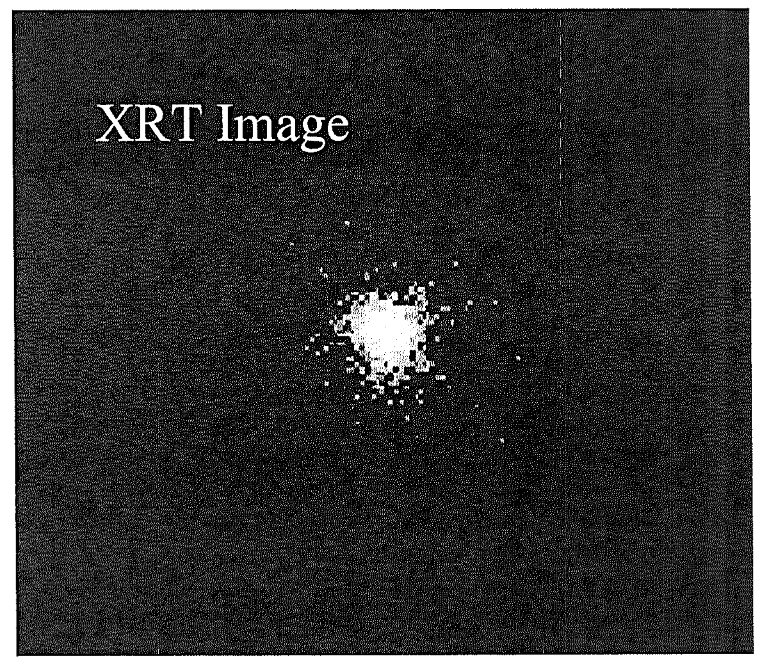
- Type C



Type A afterglow: GRB 050128

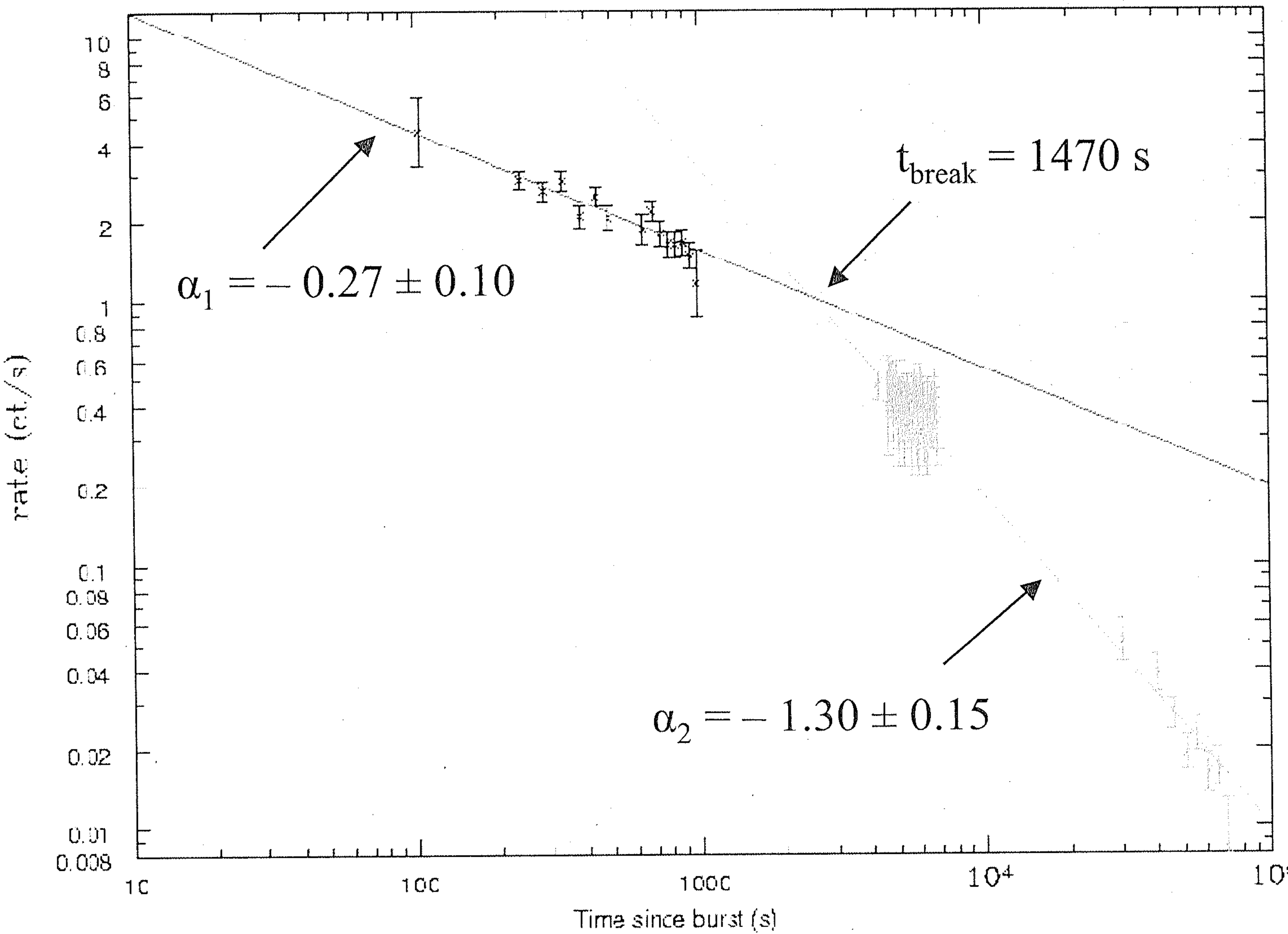


XRT in Manual State, PC Mode
- 108 s after burst trigger
- Bright, piled-up X-ray source
- Very shallow decay index in first orbit



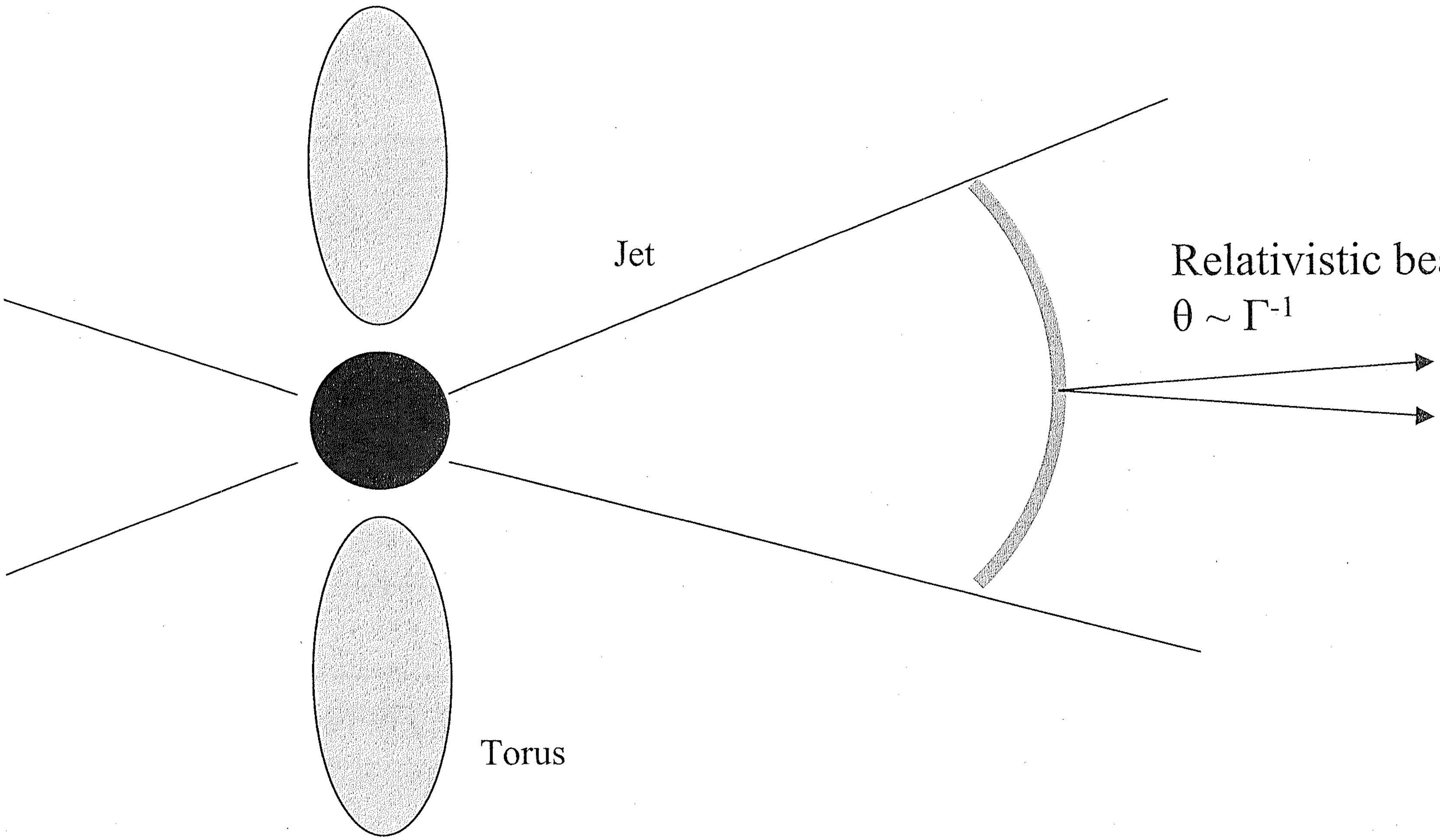
GRB 050128 XRT Lightcurve

$F_x \propto t^{\alpha}$



Campana et al. 2005, ApJL

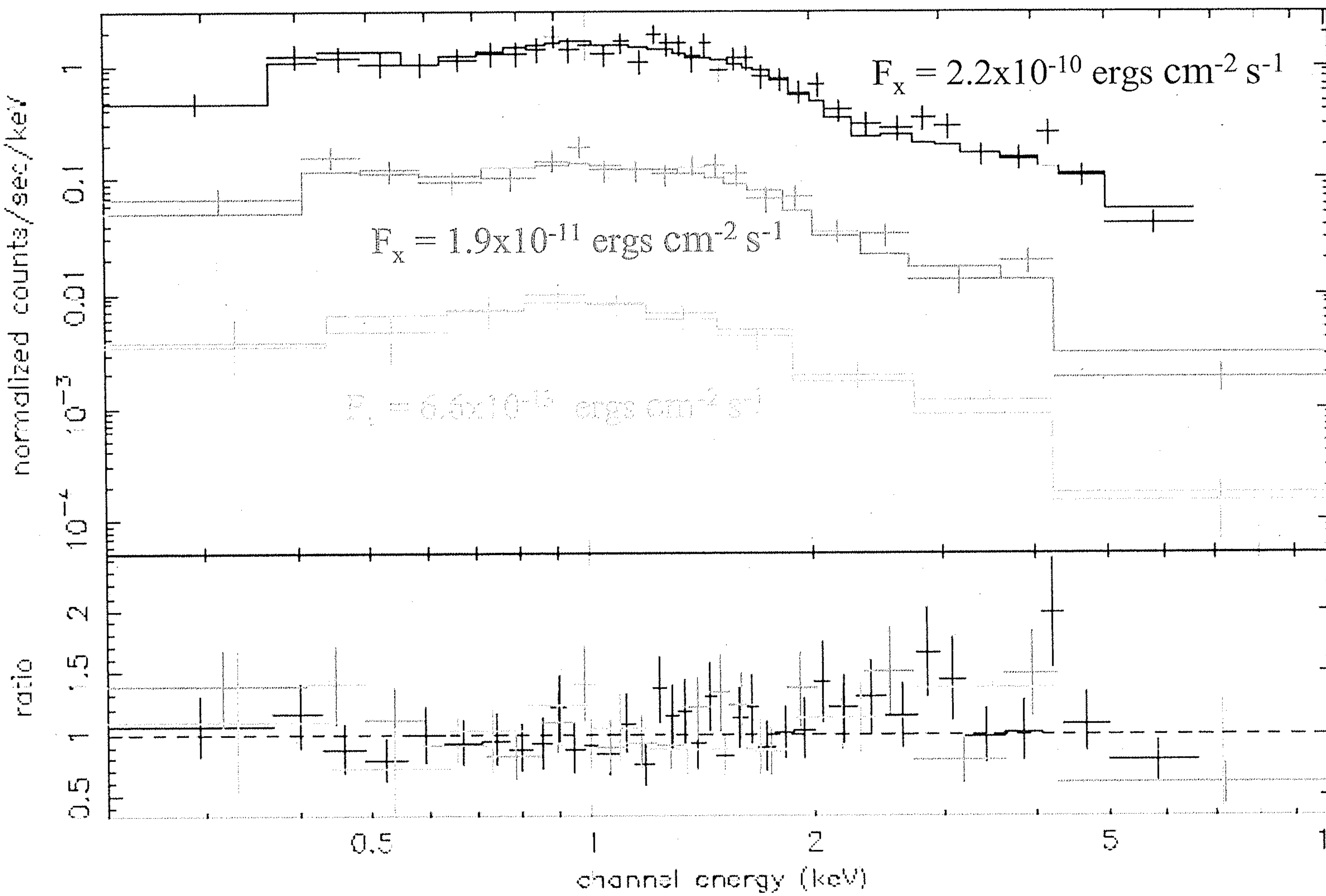
Jet Break



GRB 050128 spectrum

Photon Index=1-β = 1.66 ± 0.07

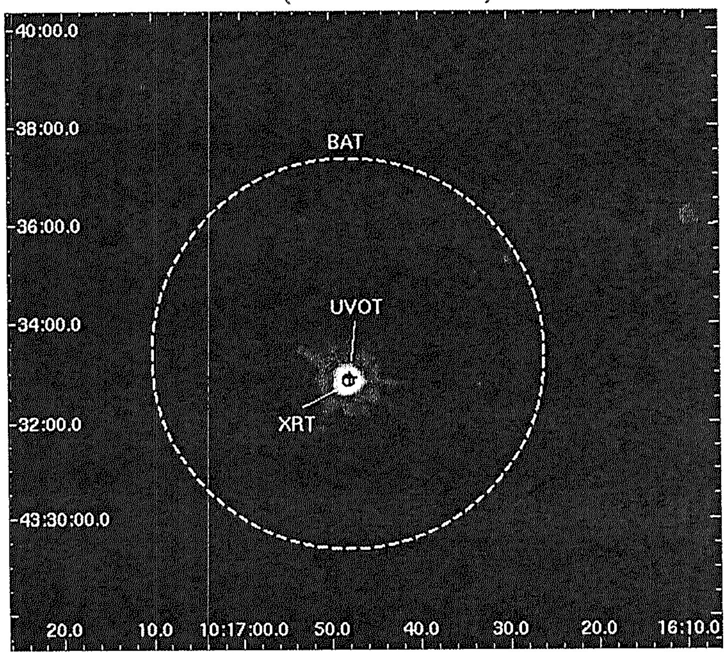
Galactic Absorbing Column = $N_H = 4.8 \times 10^{20}\ cm^{-2}$ (for all three orbits)

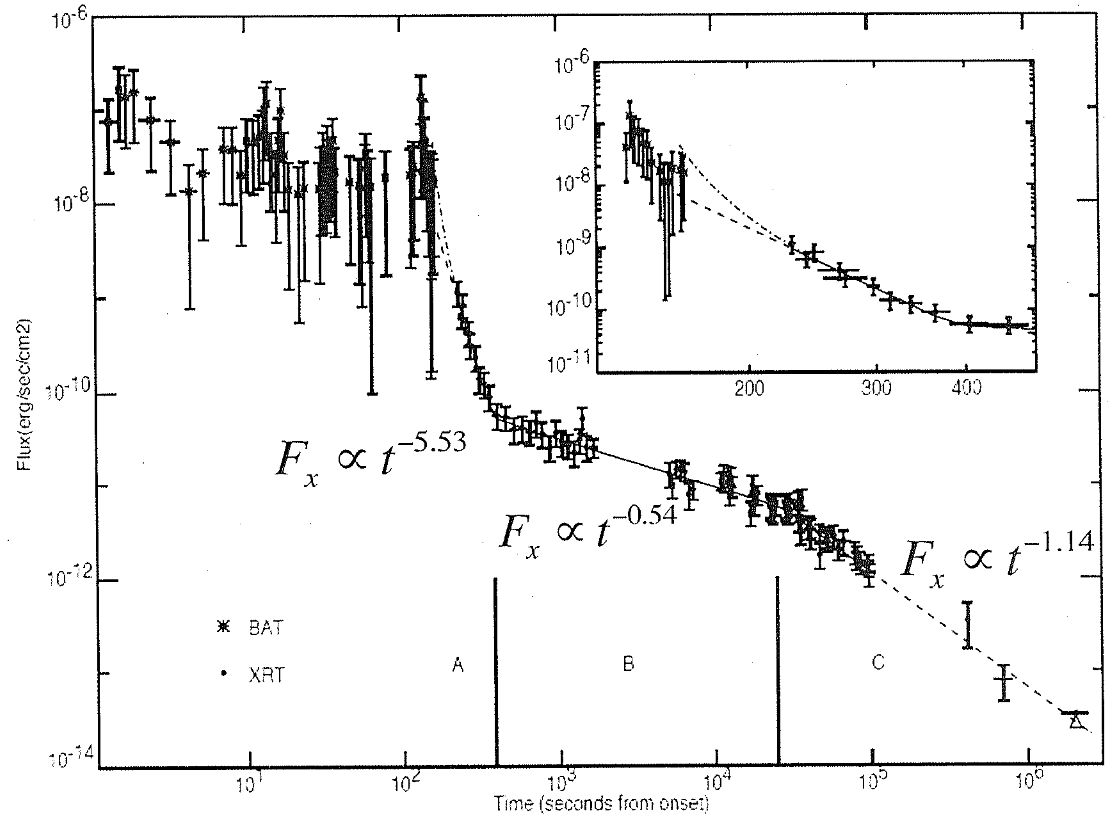


Campana et al. 2005, ApJL

Type B afterglow: GRB 050319

Detected at 09:31:18 UT
(T+ 225 s)





Source is at:
RA(J2000) = 10h 16m 48.1s,
Dec(J2000) = +43d 32' 52.3"

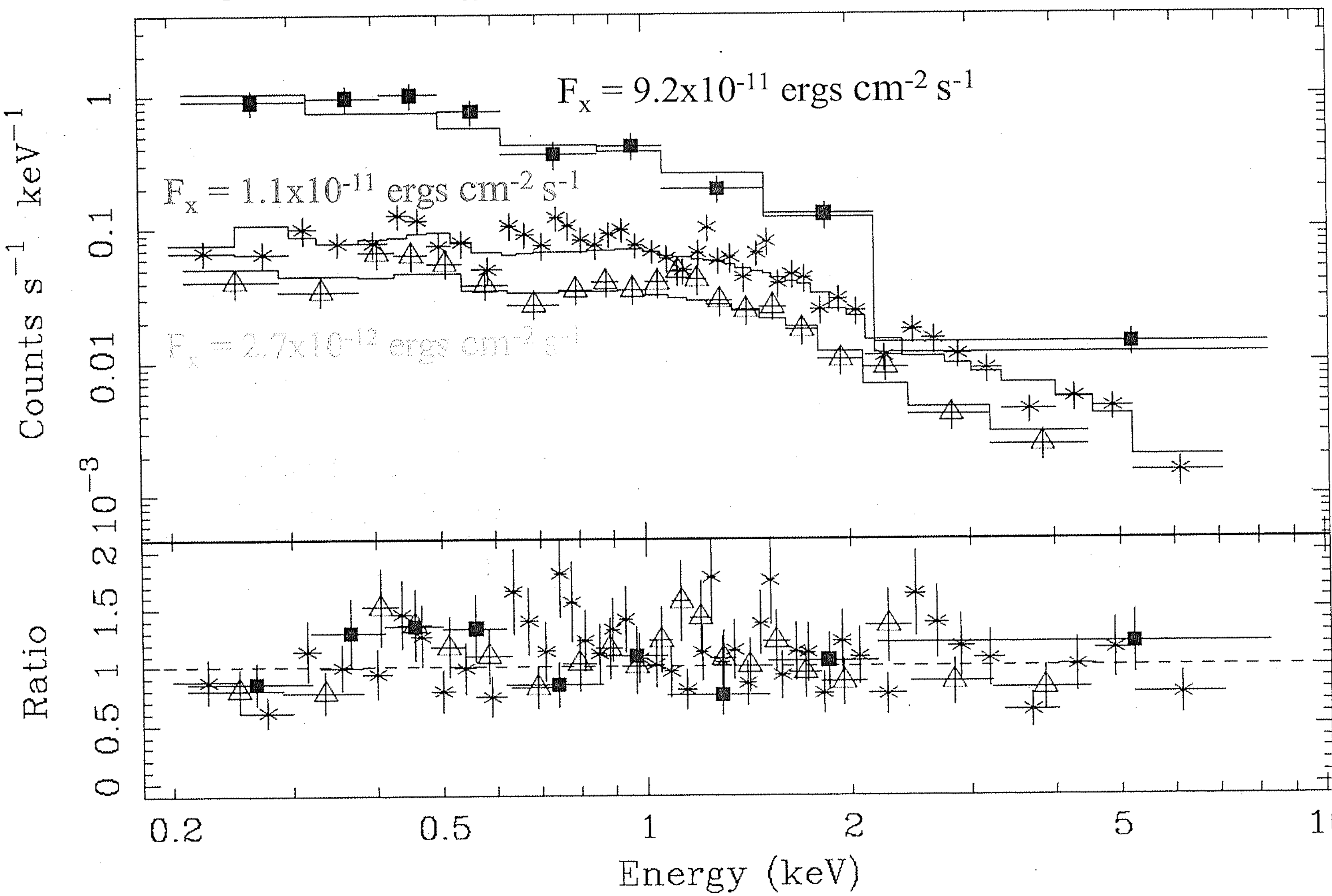
- Auto State - Determined GRB position onboard
- 3.1 arcseconds from ROTSE counterpart

Cusumano et al. 2005, ApJ

GRB 050319 Spectrum

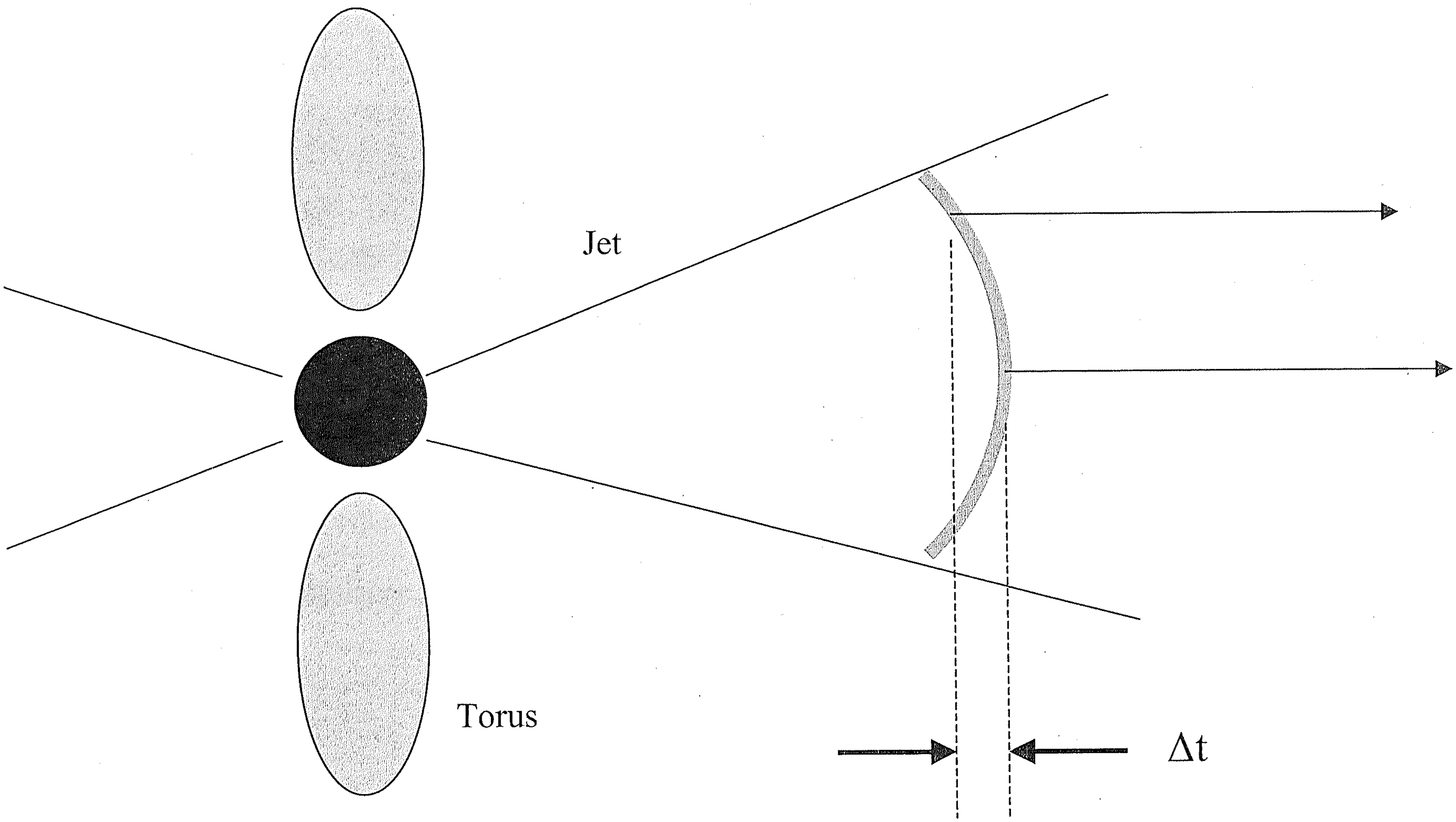
Photon index=1 - β = 2.6, 1.7 and 1.8 i.e. Starts softer and becomes harder

Galactic Absorbing Column = $N_H = 1.13 \times 10^{20}\ cm^{-2}$ (for all three phases)



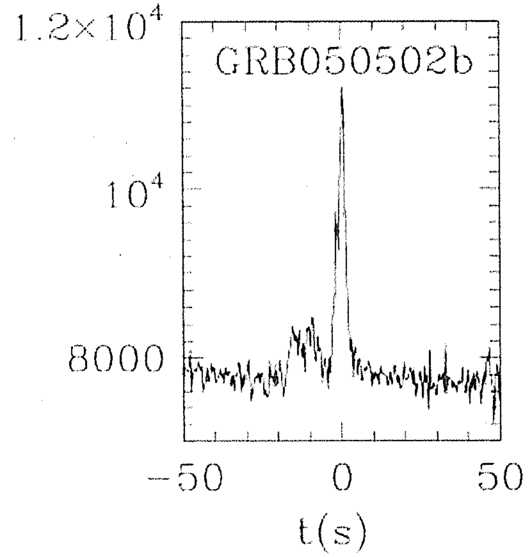
Cusumano et al. 2005, ApJ

High Latitude Emission

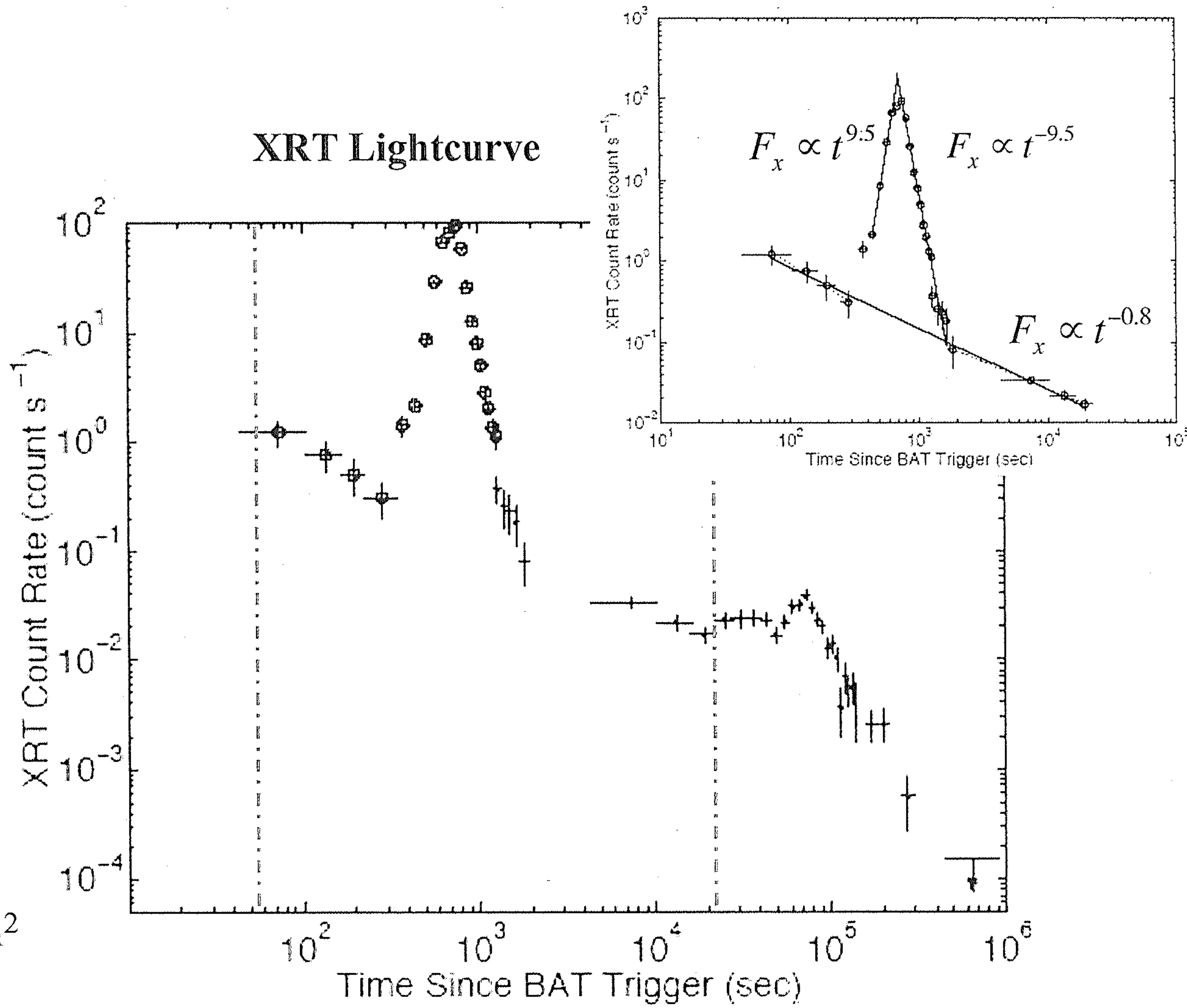


Type C: Giant X-ray Flare, GRB 050502b

BAT Lightcurve



XRT Lightcurve



GRB Fluence: 8x10^{-7} ergs/cm^2

Flare Fluence: 9x10^{-7} ergs/cm^2

Burrows et al. 2005, Science; Falcone et al. 2005, ApJ

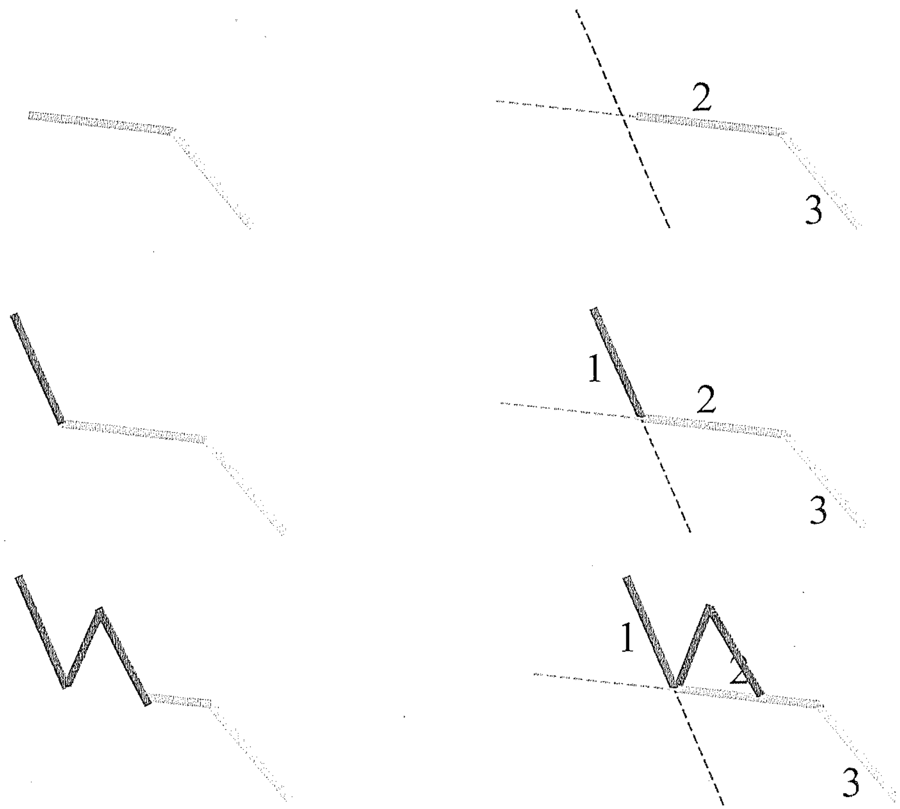
Flare Mechanism

- Rapid increase and decrease
  - Inconsistent with external shock
- Enormous increase in GRB 050502b
  - Inconsistent with Inverse Compton mechanism
- Same underlying afterglow before and after
  - Inconsistent with additional energy added to external shock
- Most likely explanation is that internal shocks continue at much later times than the prompt γ-ray emission.
  - Late-time emission occurs at larger radius, resulting in slower rise/fall and softer energies.
  - Late emission also has higher Lorentz factor because shocks expand in channel evacuated by earlier shocks.

XRT Afterglow Types

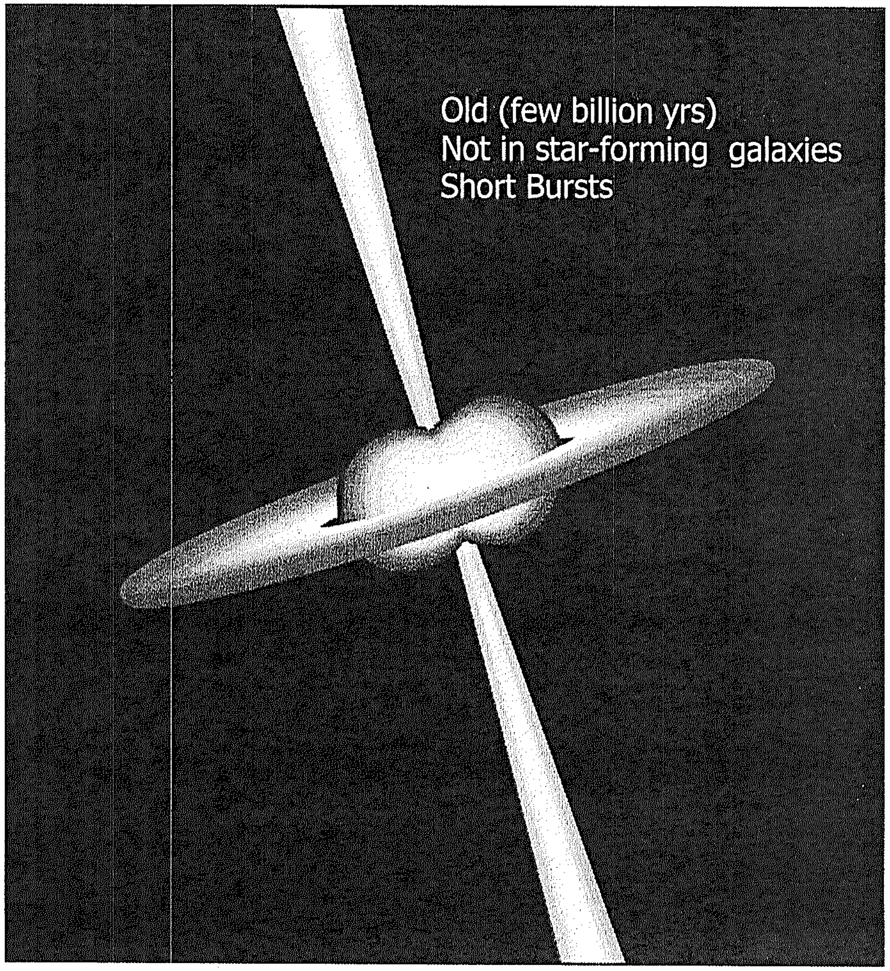
It is possible that all three types are related and we are viewing different parts of the lightcurve

- Type A
- Type B
- Type C

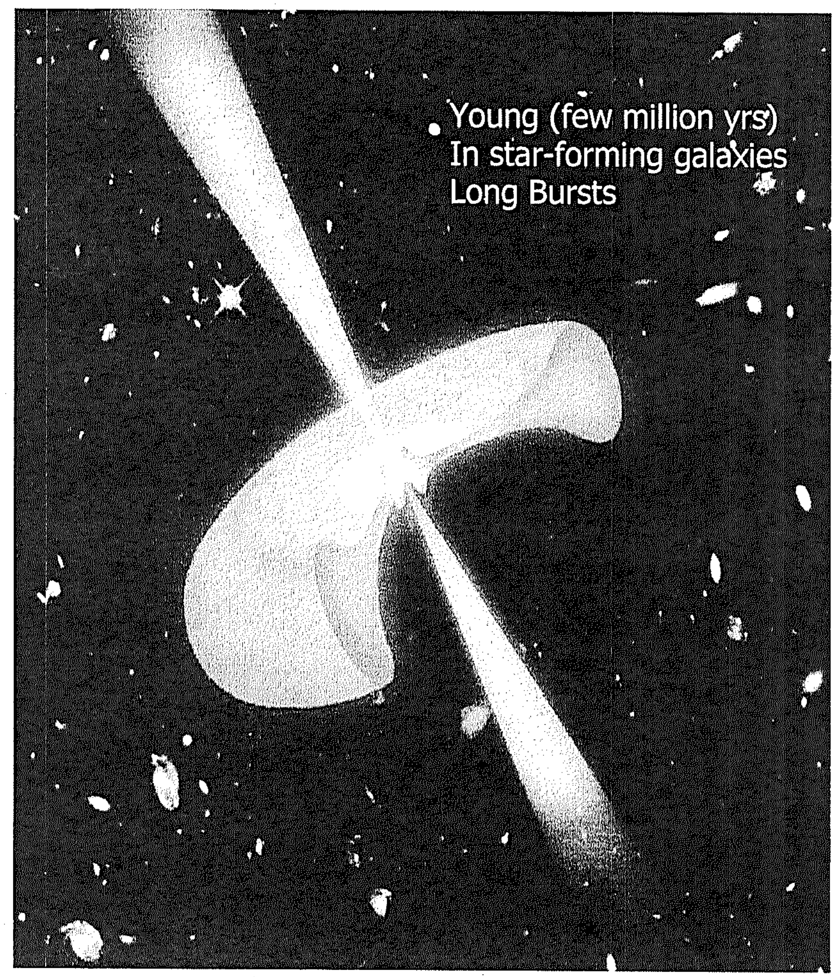


GRB Models

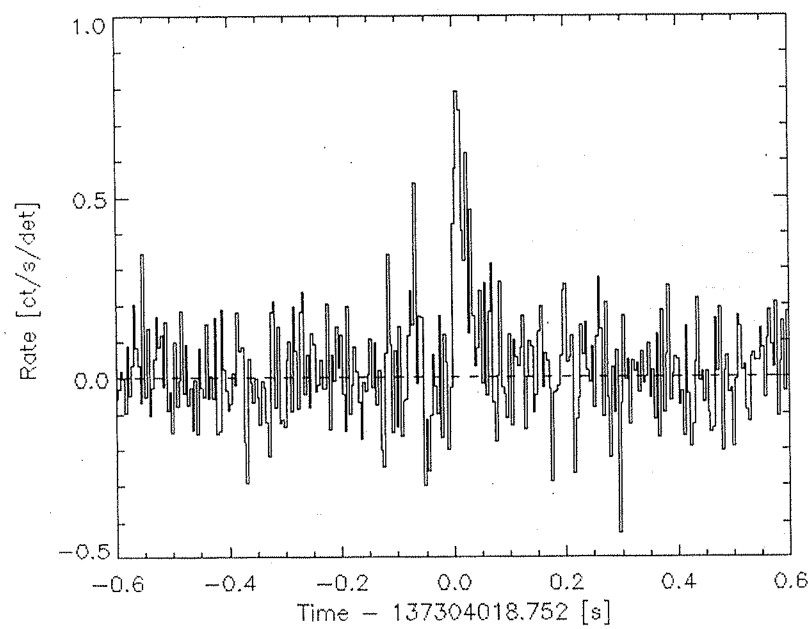
Merging Neutron Stars



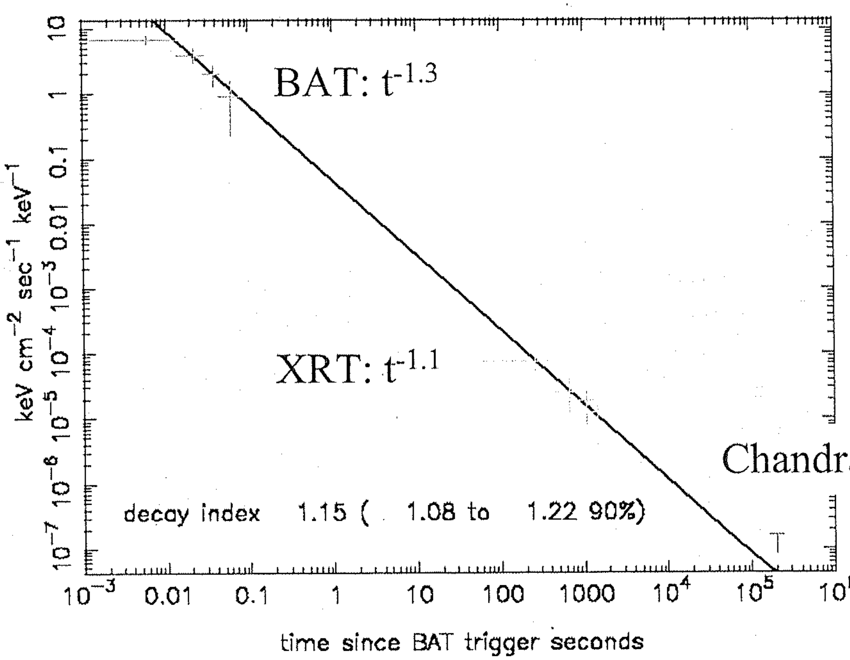
Hypernova



GRB 050509b: *First Short GRB Afterglow*



GRB050509b – Swift BAT + XRT and Chandra upper limit



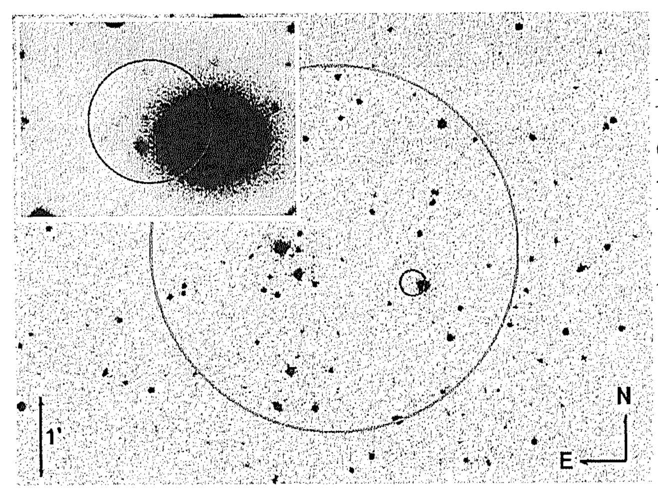
$t_{90} = 0.04$ s, Fluence = 2×10^{-8} ergs/cm^2

XRT counterpart in first 400 s, fades rapidly. 11 photons total.

Location in cluster at z=0.226, near early-type galaxy.

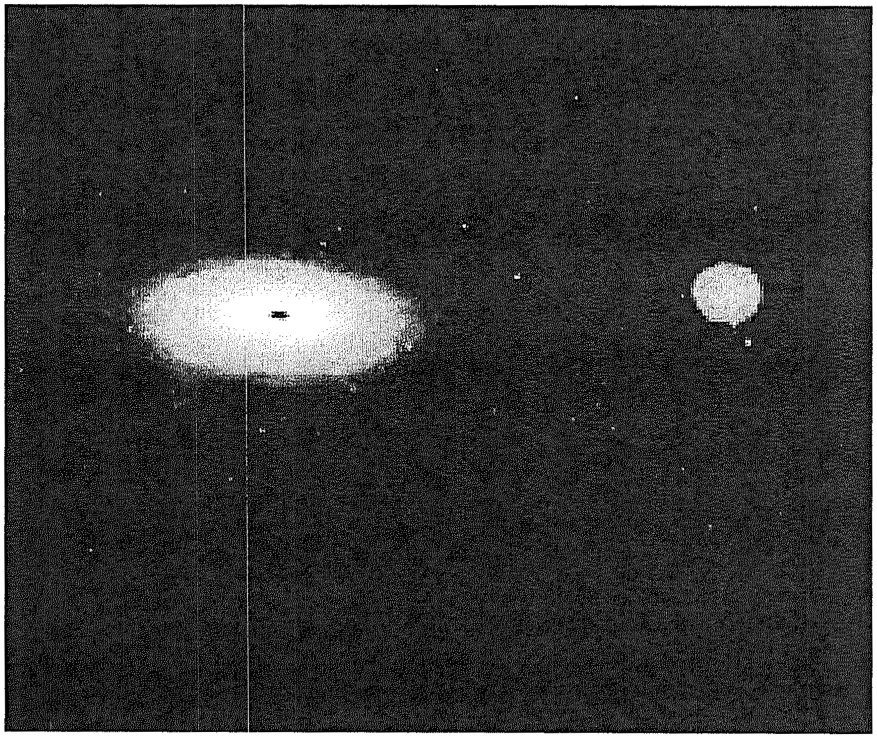
Possible NS-NS merger

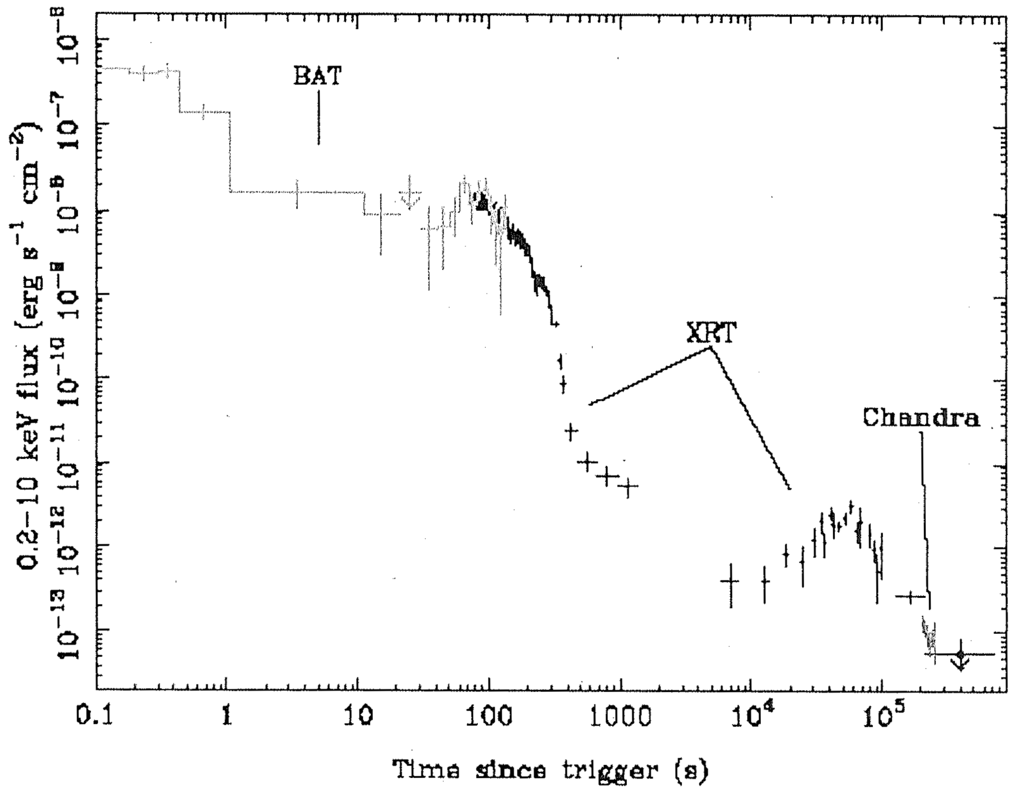
Gehrels et al. 2005, Nature



XRT error circle on VLT image. XRT position is 9.8" from a bright elliptical galaxy at z=0.226

GRB 050724: Flares in a Short GRB Afterglow





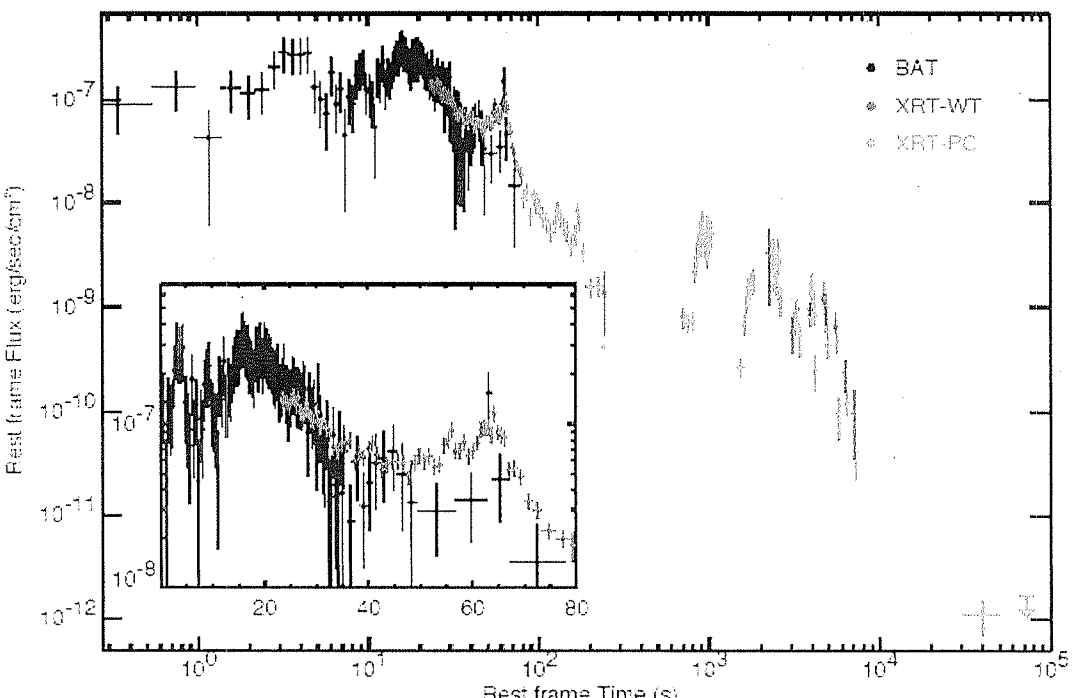
- Bright Complex lightcurve
- Associated with an elliptical galaxy
- Extended central engine activity
- Death call of a Neutron Star?

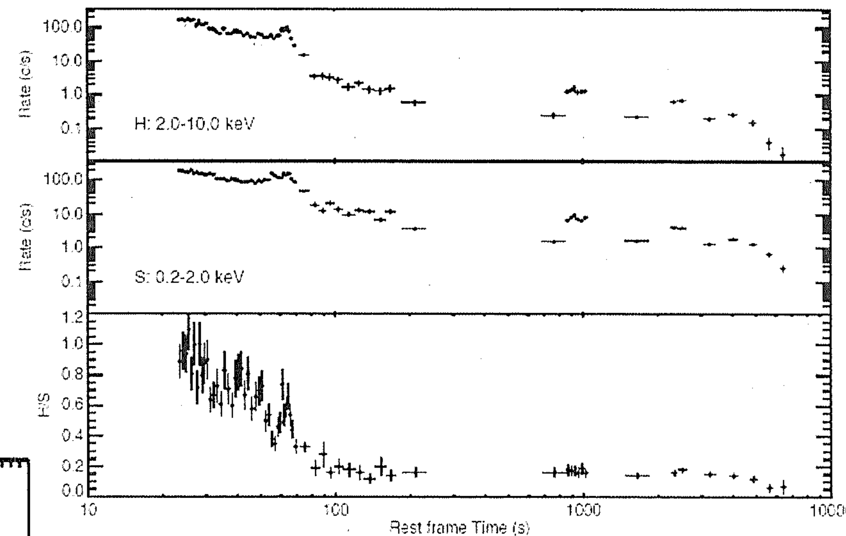
Burrows et al. 2005, Barthelmy et al. 2005, Nature

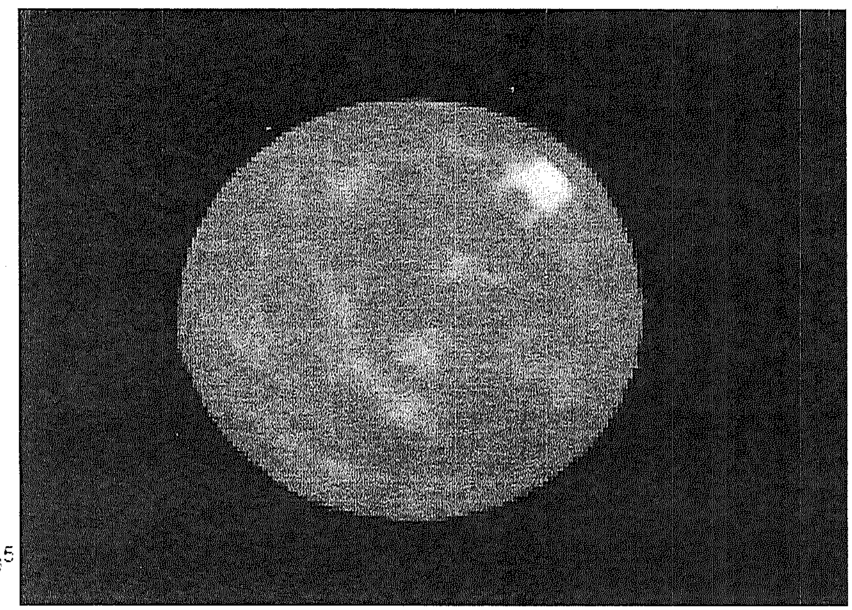
A Huge Explosion in the Early Universe

GRB 050904: Redshift of z = 6.29

- The most distant cosmic explosion ever observed
- Corresponds to 13 billion light years from Earth
- The Universe was just 700 - 750 million years old.
- Indicates the presence of massive stars only 700 million years after the big bang

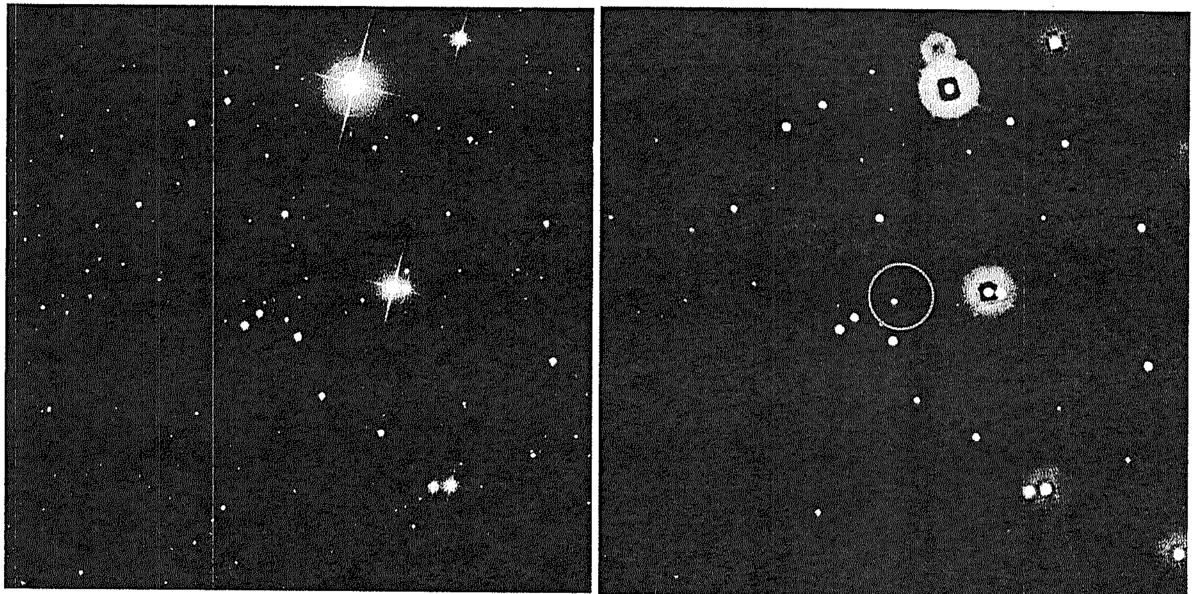




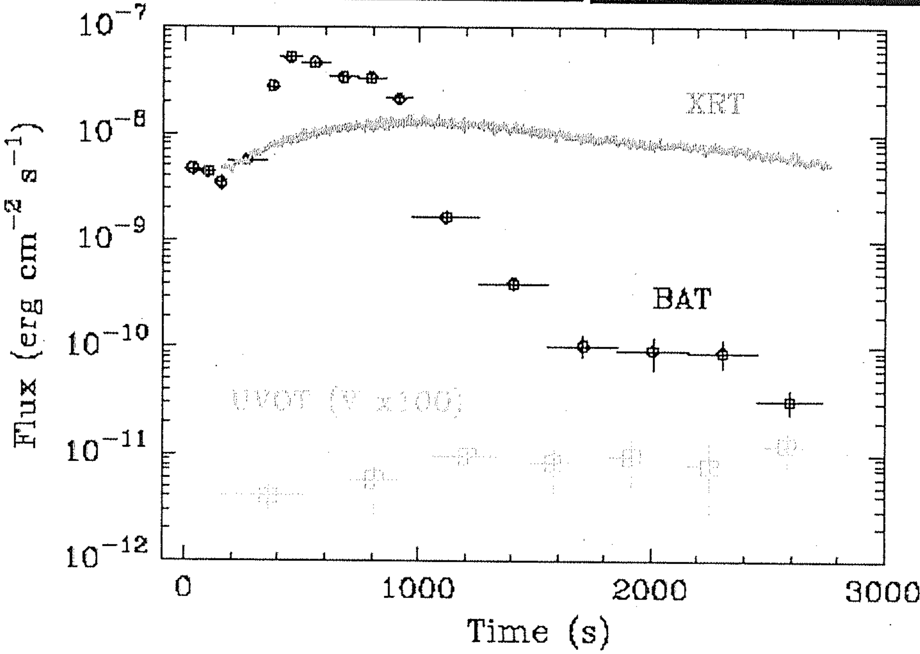


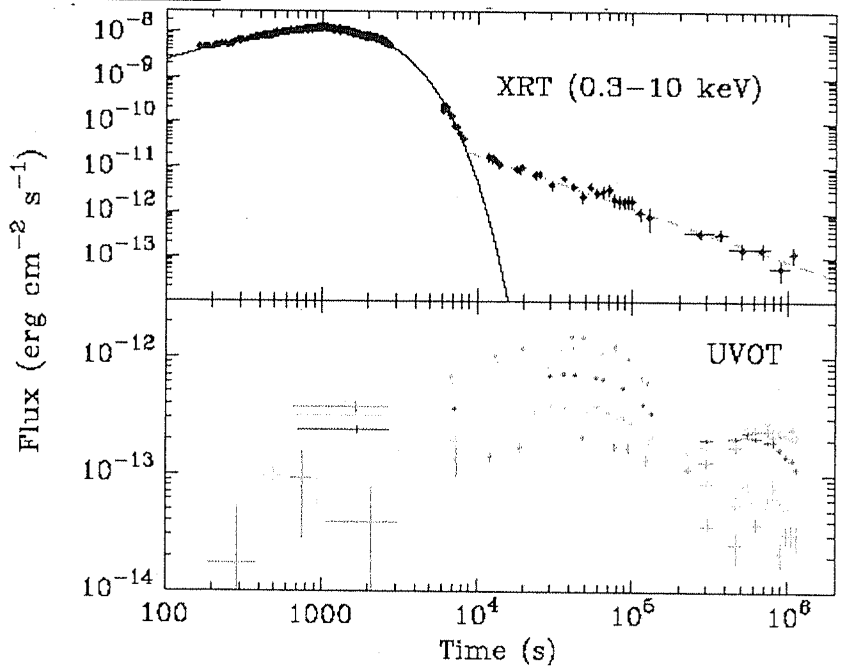
Cusumano et al. 2005, Nature

Swifts Closest GRB: GRB 060218



- RA 03:21:39.71 Dec +16:52:02.6
- 25 times closer
- 100 times longer ~2000 seconds
- Surprisingly dim
- Early optical afterglow indicates a possible SN in the works





Summary

- *Swift* has exceeded every pre-launch predicted advance in GRB science
- Discovered the farthest GRB ever seen
- Identified counterparts to Short GRBs
- Discovered new GRBs at a rate of 100/year
- Explored a brand new time interval in GRB lightcurves
  - Revealing unpredicted phenomena of GRB flares
  - Revealing unpredicted rapid X-ray afterglow declines
- As the *Swift* catalogue increases, we expect new insights into GRB formation and environments
- *Swift* has conducted >20 000 successful slews to sources and is predicted to stay in orbit until 2022
- Public data release began April 5, 2005
  - http://swift.gsfc.nasa.gov/docs/swift/sdc/

XRT Collaborators

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- Alberto Moretti
- Patrizia Romano
- Daniele Malesani
- Stefano Covino
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- Alan Wells
- Julian Osborne
- Tony Abbey
- Andy Beardmore
- Mike Goad
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- Dick Willingale
- Olivier Godet

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- Valentina Laparola

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- Lorella Angelini

UNLV:
- Bing Zhang

ASDC:
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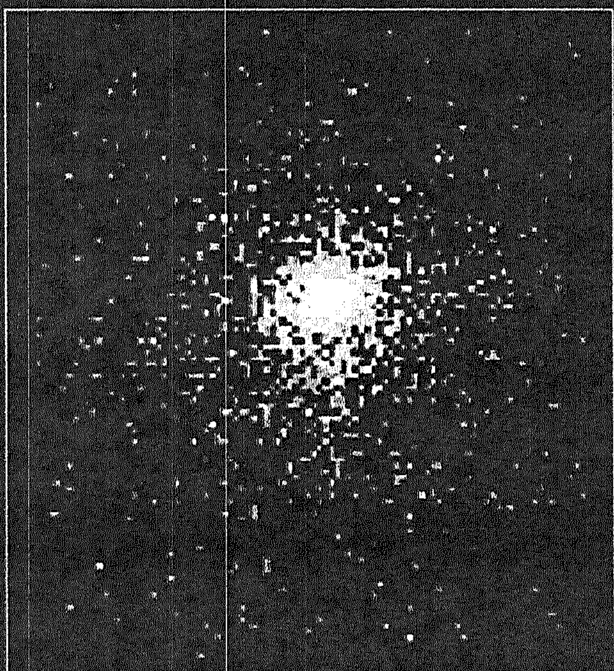
- Francesca Tamburelli
- Barbara Saija
- Milvia Capalbi
- Matteo Perri

* GSFC/USRA http://webpages.atlanticbb.net/~jeh22/

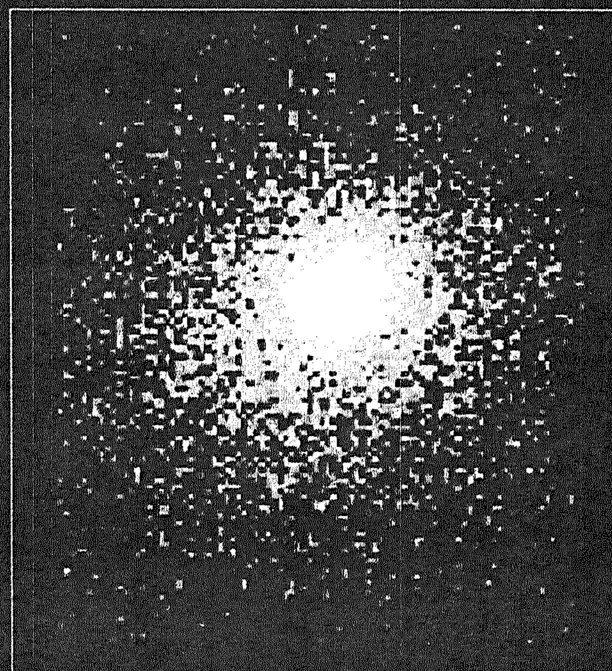
Data is public: http://swift.gsfc.nasa.gov/docs/swift/sdc/

Swift and Deep Impact Event

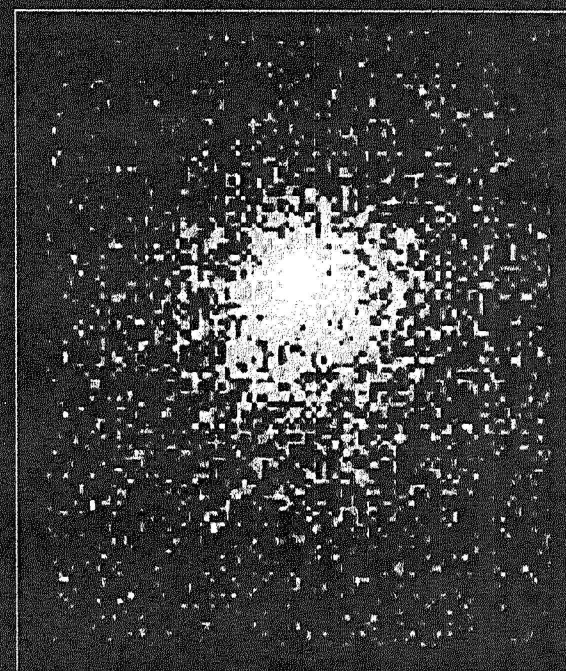
UVOT images in UVW1 filter



30 min before the impact



6 hours after the impact



34 hours after the impact

Swift Deep Impact Team